

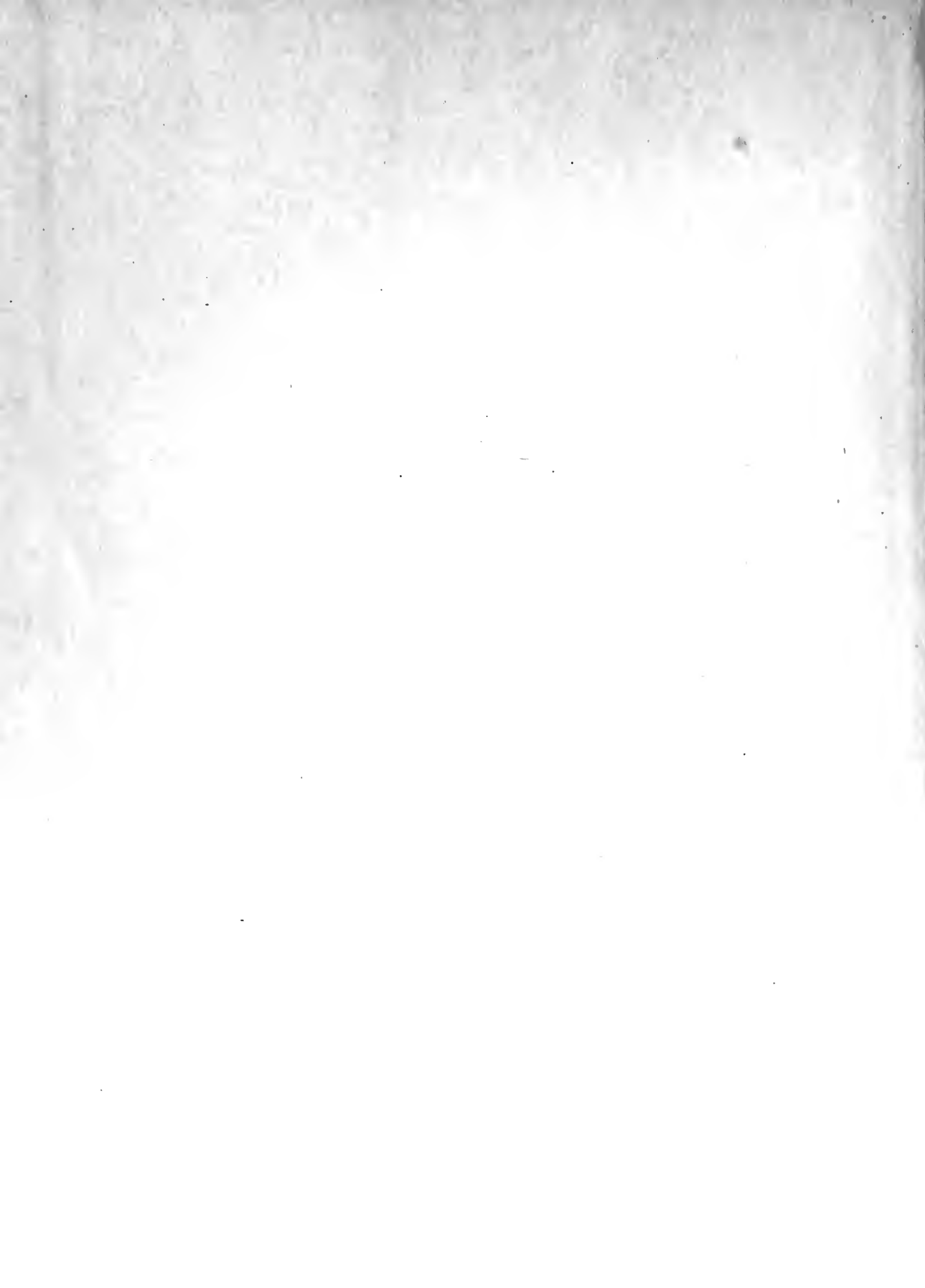
SEMI - FLEXIBLE SELF  
VARYING CAMBER RUDDER

BY  
JOHN S. EVERSOLE  
FREDERICO O. STUCKENBRUCK  
AND  
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Professor J. S. Newell  
Secretary of the Faculty  
Massachusetts Institute of Technology  
Cambridge, Massachusetts

Dear Sir:

In accordance with the requirements for the Degree of Naval Engineer,  
we submit herewith a thesis entitled "Semi-flexible Self Varying Camber  
Rudder."

Respectfully,





# SEMI-FLEXIBLE SELF VARYING CAMBER RUDDER

by

**John S. Eversole**  
**Lt. Cmdr., U.S. Navy**  
**U.S. United States Naval Academy**  
**(1939)**

and

**ACKNOWLEDGMENT**  
**Frederico O. Stuckenbruck**  
**Lieut., Brazilian Navy**

The authors wish to express their appreciation to Professors  
**U.S. Brazilian Naval Academy**  
**(1939)**

**George C. Manning, Frank M. Lewis and H. Curtis Pettit** for their valuable  
and

advice and assistance. The authors are indeed grateful to Mr. Raymond  
**Ivan G. Labouriau**

**Johnson** who assisted in the construction of the model and in the  
**Lieut., Brazilian Navy**  
**U.S. Brazilian Naval Academy**

machines work required in the course of the experimental stage of the thesis.  
**(1941)**

The authors also wish to express their appreciation to the personnel of the  
**Submitted in Partial Fulfillment of the**  
**Requirements for the Degree of**

**NAVAL ENGINEER**  
**Boston Naval Shipyard** for their assistance in the experimental equipment.  
at the

**Massachusetts Institute of Technology**  
**1950**



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### NOMENCLATURE

$C_L$  - Lift coefficient (dimensionless)

$C_D$  - Drag coefficient ( " )

$F_L$  - Lift force, lbs.

$F_D$  - Drag force, lbs.

$V$  - Water velocity, ft/sec.

$\rho$  - Water density

$S$  - Model rudder area (projected)

NOTATION

- $C_L$  - Lift coefficient (dimensionless)  
 $C_D$  - Drag coefficient ( )  
 $L$  - Lift force, lbs.  
 $D$  - Drag force, lbs.  
 $V$  - Water velocity, ft/sec.  
 $\rho$  - Water density  
 $A$  - Model target area (projected)



## I. SUMMARY

The object of the work undertaken in preparation of this thesis is the comparison of Lift and Drag Coefficients of an all metal rudder (parent) with those of a family (five) of dimensionally equal rudders which have been modified by cutting away varying percentages of the trailing edge of the parent rudder and replacing the cut away portion with rubber. In order to maintain dimensional equality, six bronze rudders were cast to the same mold, and five were modified as described above. Basic rudder characteristics are: chord - six inches, aspect ratio - one, thickness ratio - 0.19, balance - 20.8%.

Test runs were made in the M.I.T. propeller tunnel at a constant water velocity of 9 feet per second. Lift and drag forces were measured from zero to thirty five degrees angle of attack by means of strain gages mounted in the lower end of a rudder dynamometer. These forces were then converted to dimensionless lift and drag coefficients by dividing the force obtained by the product of:  $1/2(\text{water density}) \times (\text{rudder area}) \times (\text{water velocity})^2$ .

The experimental work accomplished shows that, with respect to the all metal rudder (parent), the use of a rubber trailing portion up to about 25% rubber has the effect of increasing the Lift Coefficient, the maximum increase occurring with about 12% rubber and being of the order of 2.8% increase at 30° rudder angle; 7.1% increase at 20°; 10.7% at 10°; and about 25% increase at 5° rudder. Similarly for the Drag Coefficient, a slight increase develops with increase in percentage of rubber up to about

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The object of the work undertaken in preparation of this thesis is the

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Test runs were made in the N.S.L.T. propeller tunnel at a constant water velocity of 9 feet per second. Lift and drag forces were measured from zero to thirty five degrees angle of attack by means of strain gages mounted in the lower end of a rubber dynamometer. These forces were then converted to dimensionless lift and drag coefficients by dividing the force obtained by the product of  $\frac{1}{2}(\rho \text{water density})(V^2 \text{rubber area})$ .

The experimental work accomplished shows that, with respect to the all metal rubber (patent), the use of a rubber trailing portion up to about 15% rubber has the effect of increasing the lift coefficient, the maximum increase occurring with about 10% rubber and being of the order of 1.5% increase at 30° rubber angle; 1.0% increase at 20°; and 0.5% increase at 10°. Similarly for the Drag Coefficient, a slight increase will be observed in percentage of rubber up to about

25% rubber, beyond which an increase in percentage of rubber tends to cause the Drag Coefficient to decrease. With 12% rubber the increase in the Drag Coefficient is as follows: 5.5% increase at 30° rudder angle; 6.5% increase at 20°; 13.8% increase at 10°; and 13.3% at 5° rudder angle.

If the ratio of the Lift Coefficient to the Drag Coefficient is to be used as a criterion in judging the relative performance of the rudders, it is noted that the 40% and 50% rubber rudders have considerably higher ratios than the parent rudder.

From the results of the experimental work accomplished, it is concluded that the lift Coefficient is increased, with respect to the parent (all metal rudder), with the use of a rubber trailing edge up to about 25% rubber. Beyond 25% rubber the Lift Coefficient decreases. The Drag Coefficient increases with the addition of rubber up to about 25% rubber and thereafter decreases with the use of more rubber. From a careful study of the results obtained and close observation of the rudders in the tunnel it is concluded that the rubber used was too stiff, in that it did not bend as much as was expected when subjected to the action of the water force.

In view of the results obtained from the experimental work accomplished to date with the rubber-tipped rudders, it is recommended that further experimental work be carried out with them along the following lines:

- a) Utilizing rudders with rubber of varying degrees of stiffness.
- b) Conducting a close search of the area within which the percentage of rubber varies from 5% to 15%.

15% rubber, beyond which an increase in percentage of rubber tends to cause the Drag Coefficient to decrease. With 15% rubber the increase in the Drag Coefficient is as follows: 5.5% increase at 10° rubber angle; 6.2% increase at 20°; 12.4% increase at 40°; and 13.1% at 5° rubber angle.

If the ratio of the Lift Coefficient to the Drag Coefficient is to be used as a criterion in judging the relative performance of the rubber, it is noted that the 40% and 50% rubber rubbers have considerably higher ratios than the parent rubber.

From the results of the experimental work accomplished, it is concluded that the Lift Coefficient is increased, with respect to the parent (all metal rubber), with the use of a rubber trailing edge up to about 15% rubber. Beyond 15% rubber the Lift Coefficient decreases. The Drag Coefficient increases with the addition of rubber up to about 15% rubber and thereafter decreases with the use of more rubber. From a careful study of the results obtained and close observation of the rubbers in the tunnel it is concluded that the rubber used was too stiff, in that it did not bend as much as was expected when subjected to the action of the water forces.

In view of the results obtained from the experimental work accomplished to date with the rubber-tipped rubbers, it is recommended that further experimental work be carried out with them along the following lines:

- a) Utilizing rubbers with rubber of varying degrees of stiffness.
- b) Conducting a close study of the area within which the percentage

- c) Performing experiments with all rubber rudders in which the forward part of the rudder is internally stiffened so as to be inflexible for all practical purposes, but a smooth continuous surface is presented to the flow of water around the rudder.**
- d) Investigating the effects of a ship's hull and propeller upon the behavior of rubber tipped rudders.**

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flexible for all practical purposes, but a smooth continuous surface

is presented to the flow of water around the rubber.

d) Investigating the effects of a ship's hull and propeller upon the

behavior of rubber tipped rudders.

## II. INTRODUCTION

The problem approached in the development of this thesis is the one of providing, for vessels moving through a fluid medium, a control surface which will permit adequate directional control with a minimum of undesirable effects; in the case of a rudder, this means providing maximum lift with minimum drag. The literature cited in Appendix E gives evidence of the extensive research effort directed towards this end.

The use of a rubber tipped rudder, it was thought, would permit the trailing portion of the rudder to fair into the stream of water passing it, to a certain degree, with the result that a small amount of camber would be placed on the rudder. The placement of such camber would be entirely independent of outside mechanical control or adjustment: dependent only upon the forces acting on the rubber and the stiffness of the rubber. The rubber tip would fair downstream: while the force normal to its surface might be smaller than if the surface had not bent, the athwartship component of this normal force, i.e., the lift, would be larger than if acting on a straight surface. By similar reasoning, it was believed that the longitudinal component of the force, i.e., the drag, would be less.

It was decided to experiment on a comparative basis, using one all metal rudder as the basis of comparison; a parent rudder, so to speak. Then five more rudders would be made from the same mold as the parent rudder but with 10%, 20%, 30%, 40%, and 50% of the rudder surface replaced with rubber. The rubber of all rudders was to be cut from the same sheet, to insure that the same rubber characteristics were present

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on all rubber-tipped rudders.

An order for the manufacture of the six rudders was placed with the Boston Naval Shipyard and in due time all six rudders were manufactured. The metal portion was "Composition G Bronze" and the rubber was cut from a sheet of gasket material and cemented to the metal with deck tread cement. While the job order called for a rubber percentage of 10%, 20%, 30%, 40%, and 50%, it was found upon careful measurement that, due to manufacturing errors, the actual percentages of exposed rubber, as measured along the side of the rudders, were as follows:

ORDERED	RECEIVED
0%	0%
10%	15.4%
20%	25.0%
30%	33.5%
40%	40.7%
50%	48.7%

Throughout this thesis the rudders are referred to as 10%, 20%, 30%, 40%, and 50% rubber. It should be borne in mind that the actual percentages are as listed above, under the RECEIVED column.

The actual rudder dimensions are as shown in Figure XI.

Due to the necessity of hand finishing the rubber portion of the rudders, there were slight differences found between rudders, but not of such an extent as to invalidate the comparative results obtained from the experiments. It is worthy of note, however, that due to the construction of the joint between the metal and the rubber, a continuous smooth surface for presentation to the flow of water was not attained, with possible attendant effect on drag components.

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RECEIVED	ORDERED
10%	10%
12.4%	10%
14.0%	10%
17.4%	10%
40.1%	40%
48.1%	50%

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The actual rubber dimensions are as shown in Figure XI. Due to the necessity of hand fitting the rubber portion of the rubbers, there were slight differences found between rubbers, but not of such an extent as to invalidate the comparative results obtained from the experiments. It is worthy of note, however, that due to the construction of the joint between the metal and the rubber, a continuous smooth surface for presentation to the flow of water was not attained, with possible attendant effect on drag.

The forces acting on the rudder were to be measured by the dynamometer developed and built by Kissinger & Rupp, and described in Appendix A.

The rubber swim fins used by swimmers in gaining ahead thrust, and the shape of racing shell oars used to gain "negative drag" were factors given consideration in the development of the idea of semi-flexible rudders. This same idea was also strengthened by some of the facts found in Nature, such as the extreme mobility of fish tails and the softer feather tips in the trailing edge of birds' wings.

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### III. PROCEDURE

The first step to be accomplished in the experimental work was accurate calibration of the rudder dynamometer. This was performed by placing the dynamometer in a test rack outside the tunnel and by applying known forces to the rudder stock in a direction which would be parallel to the flow of water, with the dynamometer in the tunnel, and in a direction perpendicular thereto. Calibration curves were then prepared as in Figure XII. With the rudder in the tunnel, strain gage readings of deflections in micro-inches were then easily converted to pounds force.

Water speed to be used throughout the experiment was set at 9 ft/sec. in order to stay well within the forces used in the calibration of the dynamometer. During the running of the tests, the water speed was kept under constant monitoring to insure that it was maintained at exactly 9 ft/sec., which corresponds to a Reynolds number of 371,600 (for fresh water at 60°F).

Due to the construction of the dynamometer, the range of rudder angle that could be applied was from 10 degrees left rudder to 36 degrees right rudder.

A "run" consisted of measuring lift and drag forces every few degrees: 3, 5, 7, 10, 13, 15, 17, etc., over the full range of the dynamometer. The location of "zero rudder" was determined by the point at which the Lift Force curve of the run being made crossed the zero axis, going from positive to negative. The Lift and Drag Forces were converted

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A "pan" consisted of measuring lift and drag forces every few degrees: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99, 100, 101, 102, 103, 104, 105, 106, 107, 108, 109, 110, 111, 112, 113, 114, 115, 116, 117, 118, 119, 120, 121, 122, 123, 124, 125, 126, 127, 128, 129, 130, 131, 132, 133, 134, 135, 136, 137, 138, 139, 140, 141, 142, 143, 144, 145, 146, 147, 148, 149, 150, 151, 152, 153, 154, 155, 156, 157, 158, 159, 160, 161, 162, 163, 164, 165, 166, 167, 168, 169, 170, 171, 172, 173, 174, 175, 176, 177, 178, 179, 180, 181, 182, 183, 184, 185, 186, 187, 188, 189, 190, 191, 192, 193, 194, 195, 196, 197, 198, 199, 200, 201, 202, 203, 204, 205, 206, 207, 208, 209, 210, 211, 212, 213, 214, 215, 216, 217, 218, 219, 220, 221, 222, 223, 224, 225, 226, 227, 228, 229, 230, 231, 232, 233, 234, 235, 236, 237, 238, 239, 240, 241, 242, 243, 244, 245, 246, 247, 248, 249, 250, 251, 252, 253, 254, 255, 256, 257, 258, 259, 260, 261, 262, 263, 264, 265, 266, 267, 268, 269, 270, 271, 272, 273, 274, 275, 276, 277, 278, 279, 280, 281, 282, 283, 284, 285, 286, 287, 288, 289, 290, 291, 292, 293, 294, 295, 296, 297, 298, 299, 300, 301, 302, 303, 304, 305, 306, 307, 308, 309, 310, 311, 312, 313, 314, 315, 316, 317, 318, 319, 320, 321, 322, 323, 324, 325, 326, 327, 328, 329, 330, 331, 332, 333, 334, 335, 336, 337, 338, 339, 340, 341, 342, 343, 344, 345, 346, 347, 348, 349, 350, 351, 352, 353, 354, 355, 356, 357, 358, 359, 360, 361, 362, 363, 364, 365, 366, 367, 368, 369, 370, 371, 372, 373, 374, 375, 376, 377, 378, 379, 380, 381, 382, 383, 384, 385, 386, 387, 388, 389, 390, 391, 392, 393, 394, 395, 396, 397, 398, 399, 400, 401, 402, 403, 404, 405, 406, 407, 408, 409, 410, 411, 412, 413, 414, 415, 416, 417, 418, 419, 420, 421, 422, 423, 424, 425, 426, 427, 428, 429, 430, 431, 432, 433, 434, 435, 436, 437, 438, 439, 440, 441, 442, 443, 444, 445, 446, 447, 448, 449, 450, 451, 452, 453, 454, 455, 456, 457, 458, 459, 460, 461, 462, 463, 464, 465, 466, 467, 468, 469, 470, 471, 472, 473, 474, 475, 476, 477, 478, 479, 480, 481, 482, 483, 484, 485, 486, 487, 488, 489, 490, 491, 492, 493, 494, 495, 496, 497, 498, 499, 500, 501, 502, 503, 504, 505, 506, 507, 508, 509, 510, 511, 512, 513, 514, 515, 516, 517, 518, 519, 520, 521, 522, 523, 524, 525, 526, 527, 528, 529, 530, 531, 532, 533, 534, 535, 536, 537, 538, 539, 540, 541, 542, 543, 544, 545, 546, 547, 548, 549, 550, 551, 552, 553, 554, 555, 556, 557, 558, 559, 560, 561, 562, 563, 564, 565, 566, 567, 568, 569, 570, 571, 572, 573, 574, 575, 576, 577, 578, 579, 580, 581, 582, 583, 584, 585, 586, 587, 588, 589, 590, 591, 592, 593, 594, 595, 596, 597, 598, 599, 600, 601, 602, 603, 604, 605, 606, 607, 608, 609, 610, 611, 612, 613, 614, 615, 616, 617, 618, 619, 620, 621, 622, 623, 624, 625, 626, 627, 628, 629, 630, 631, 632, 633, 634, 635, 636, 637, 638, 639, 640, 641, 642, 643, 644, 645, 646, 647, 648, 649, 650, 651, 652, 653, 654, 655, 656, 657, 658, 659, 660, 661, 662, 663, 664, 665, 666, 667, 668, 669, 670, 671, 672, 673, 674, 675, 676, 677, 678, 679, 680, 681, 682, 683, 684, 685, 686, 687, 688, 689, 690, 691, 692, 693, 694, 695, 696, 697, 698, 699, 700, 701, 702, 703, 704, 705, 706, 707, 708, 709, 710, 711, 712, 713, 714, 715, 716, 717, 718, 719, 720, 721, 722, 723, 724, 725, 726, 727, 728, 729, 730, 731, 732, 733, 734, 735, 736, 737, 738, 739, 740, 741, 742, 743, 744, 745, 746, 747, 748, 749, 750, 751, 752, 753, 754, 755, 756, 757, 758, 759, 760, 761, 762, 763, 764, 765, 766, 767, 768, 769, 770, 771, 772, 773, 774, 775, 776, 777, 778, 779, 780, 781, 782, 783, 784, 785, 786, 787, 788, 789, 790, 791, 792, 793, 794, 795, 796, 797, 798, 799, 800, 801, 802, 803, 804, 805, 806, 807, 808, 809, 810, 811, 812, 813, 814, 815, 816, 817, 818, 819, 820, 821, 822, 823, 824, 825, 826, 827, 828, 829, 830, 831, 832, 833, 834, 835, 836, 837, 838, 839, 840, 841, 842, 843, 844, 845, 846, 847, 848, 849, 850, 851, 852, 853, 854, 855, 856, 857, 858, 859, 860, 861, 862, 863, 864, 865, 866, 867, 868, 869, 870, 871, 872, 873, 874, 875, 876, 877, 878, 879, 880, 881, 882, 883, 884, 885, 886, 887, 888, 889, 890, 891, 892, 893, 894, 895, 896, 897, 898, 899, 900, 901, 902, 903, 904, 905, 906, 907, 908, 909, 910, 911, 912, 913, 914, 915, 916, 917, 918, 919, 920, 921, 922, 923, 924, 925, 926, 927, 928, 929, 930, 931, 932, 933, 934, 935, 936, 937, 938, 939, 940, 941, 942, 943, 944, 945, 946, 947, 948, 949, 950, 951, 952, 953, 954, 955, 956, 957, 958, 959, 960, 961, 962, 963, 964, 965, 966, 967, 968, 969, 970, 971, 972, 973, 974, 975, 976, 977, 978, 979, 980, 981, 982, 983, 984, 985, 986, 987, 988, 989, 990, 991, 992, 993, 994, 995, 996, 997, 998, 999, 1000.

to dimensionless coefficients as defined in hydromechanics literature:

$$C_L = \frac{F_L}{1/2 \rho S V^2} \quad C_D = \frac{F_D}{1/2 \rho S V^2}$$

Three complete runs for all rudders were made, with three additional runs made on the parent all metal rudder in order to insure that the basis for comparison of the remaining family of rudders was sound and accurate. Numerous checks of various points on the Lift and Drag curves were made to insure that consistent results were being obtained.

The calibration of the dynamometer was checked repeatedly during the course of the experimental work.

Upon the completion of the experimental work, the results were plotted in the form of curves of rudder angle vs. Lift and Drag Coefficients for all six rudders and of the following cross curves:

Lift Coefficient vs. Percent Rubber

Drag coefficient vs. Percent Rubber

Lift Coefficient/Drag Coefficient vs. Rudder Angle

to dimensional coefficients as defined in hydrodynamic literature

$$C_L = \frac{1.56 \times 10^{-4}}{1.56 \times 10^{-4}} \quad C_D = \frac{1.56 \times 10^{-4}}{1.56 \times 10^{-4}}$$

Three complete runs for all rubbers were made, with three additional runs made on the parent all metal rubber in order to insure that the basis for comparison of the remaining family of rubbers was sound and accurate. Numerous checks of various points on the Lift and Drag curves were made to insure that consistent results were being obtained.

The calibration of the dynamometer was checked repeatedly during the course of the experimental work.

Upon the completion of the experimental work, the results were plotted in the form of curves of rubber angle vs. Lift and Drag Coefficients for all six rubbers and of the following cross curves:

- Lift Coefficient vs. Percent Rubber
- Drag Coefficient vs. Percent Rubber
- Lift Coefficient/Drag Coefficient vs. Rubber Angle



#### IV. RESULTS

The results of the experimental work involved in this thesis are shown in the curves on Figures I to X, inclusive. The only variable quantities entering into the results are the percentage of rubber on each rudder and the water density. The water density was corrected for temperature throughout. The velocity of the water was kept constant at 9 ft/sec. The area of all rudders is taken as 36 square inches, i.e., projected area (12).

Observation of the experimental runs in progress showed that the rubber did not flex nearly as much as was anticipated, indicating that the rubber used was too stiff. With 50% rubber a slight but definite deflection was noticed.

A galvanometer was used to indicate balance in the SR-4 Strain Gage Indicator, in measuring forces on the rudder. It was anticipated that with the rubber tips on the rudders there would be a considerable amount of flutter or vibration, which would show on the galvanometer, probably making it difficult to balance. This, however, was not the case. In measuring lift, the amount of vibration appeared to be about the same for both the solid and rubber-tipped rudders. In measuring drag, it was found that the rubber-tipped rudders gave remarkably more steady readings than were given by the all metal rudder.

Figures I to VI are individual plots for each rudder. Figures VII to X give comparative results among the rudders in the form of cross-curves and multiple plots.

#### IV. RESULTS

The results of the experimental work involved in this thesis are shown in the curves on Figures I to X, inclusive. The only variable quantities entering into the results are the percentage of rubber on each wedge and the water density. The water density was corrected for temperature throughout. The velocity of the water was kept constant at 9 in/sec. The area of all rubbers is taken as 36 square inches, i.e., projected area (15). Observation of the experimental runs in progress showed that the rubber did not flex nearly as much as was anticipated, indicating that the rubber used was too stiff. With 50% rubber a slight but definite deflection was noticed. A galvanometer was used to indicate balance in the 25-4 strain gauge indicator, in measuring forces on the rubber. It was anticipated that with the rubber tips on the rubbers there would be a considerable amount of friction or vibration, which would show on the galvanometer, probably making it difficult to balance. This, however, was not the case, in measuring the amount of vibration appeared to be about the same for both the solid and rubber-tipped rubbers. In measuring drag, it was found that the rubber-tipped rubbers gave remarkably more steady readings than were given by the all metal rubber. Figures I to VI are individual plots for each rubber. Figures VII to X give comparative results among the rubbers in the form of cross-curves and multiple plots.

FIGURE 1

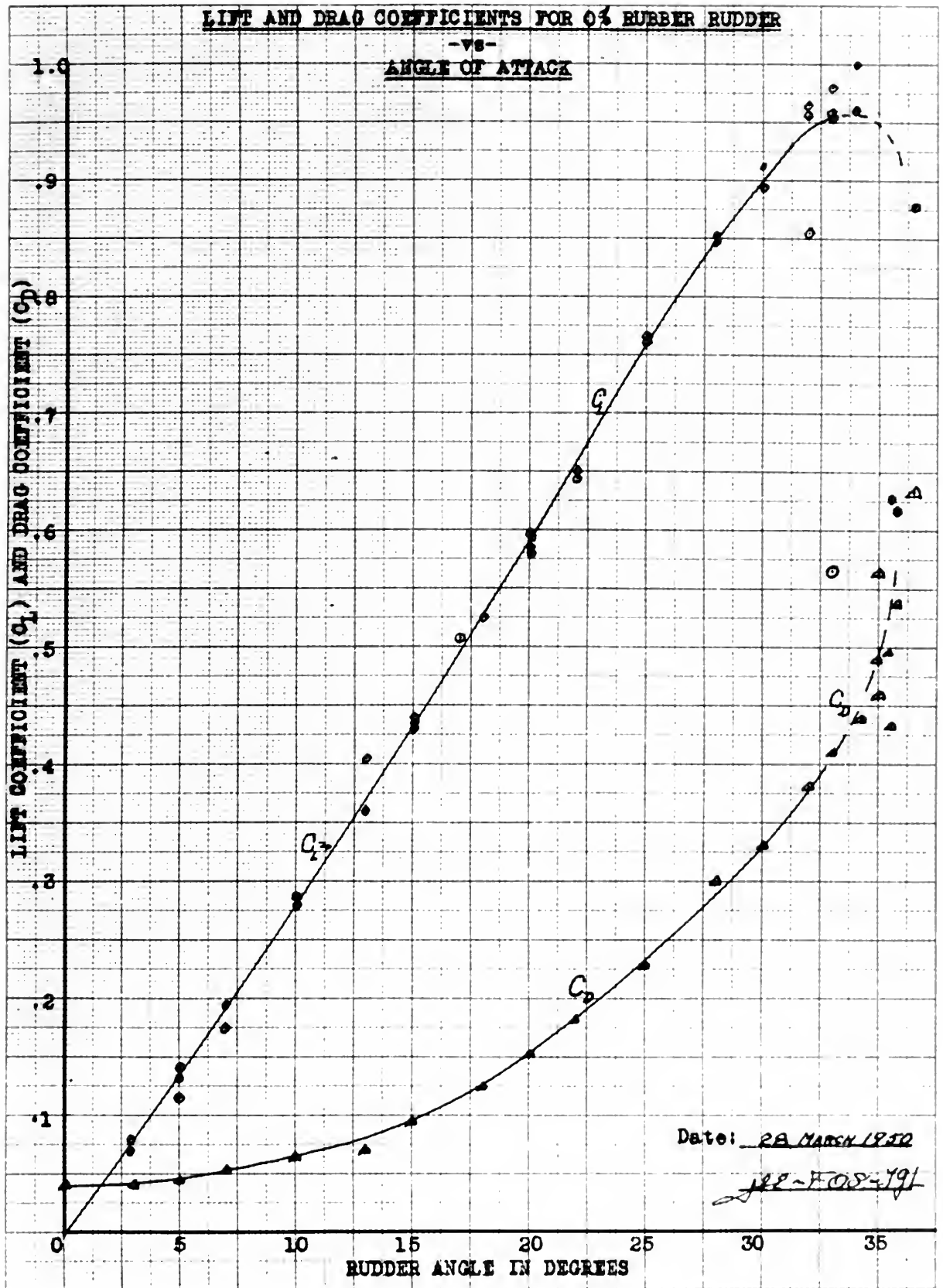




FIGURE II

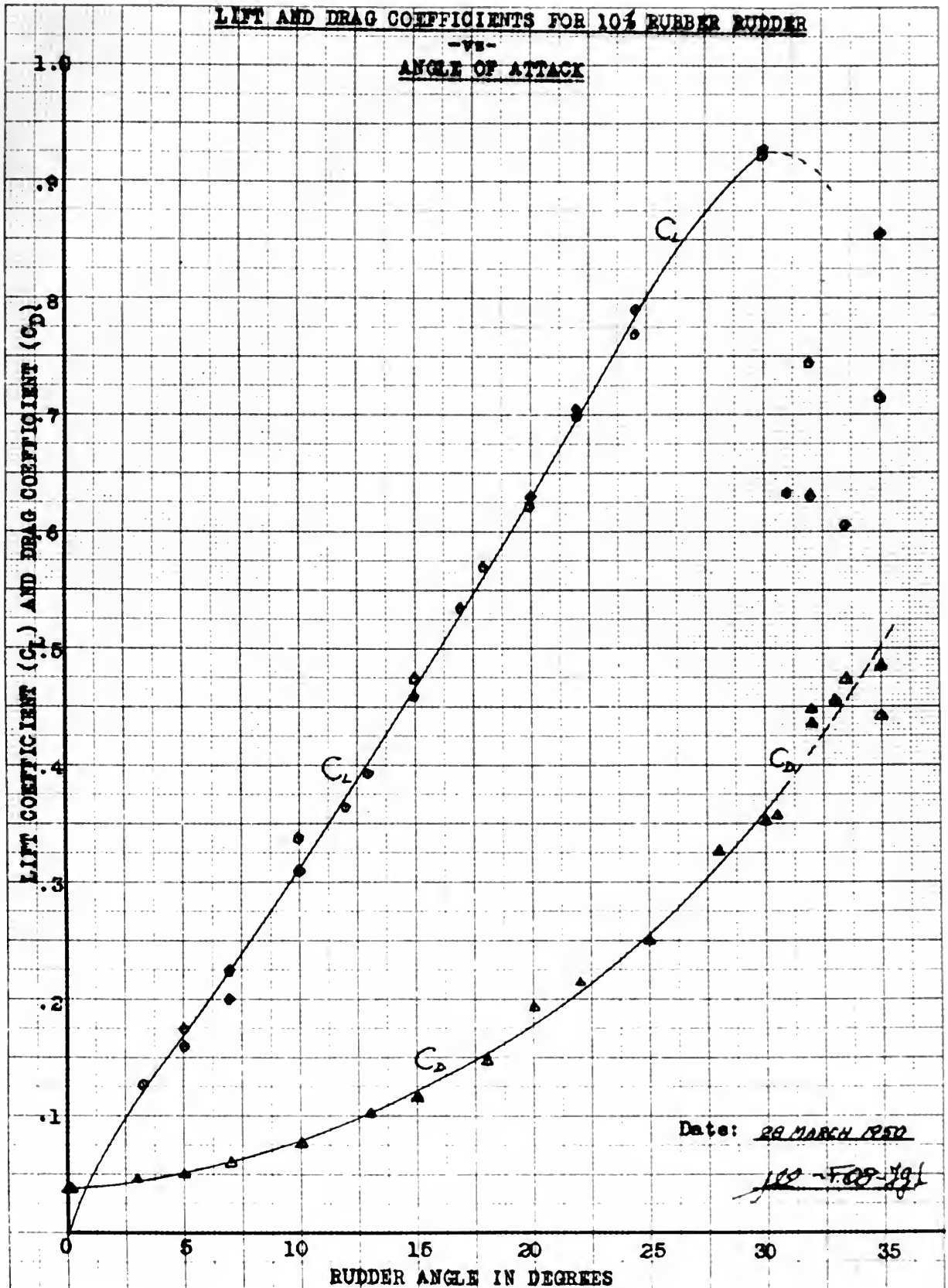




FIGURE III

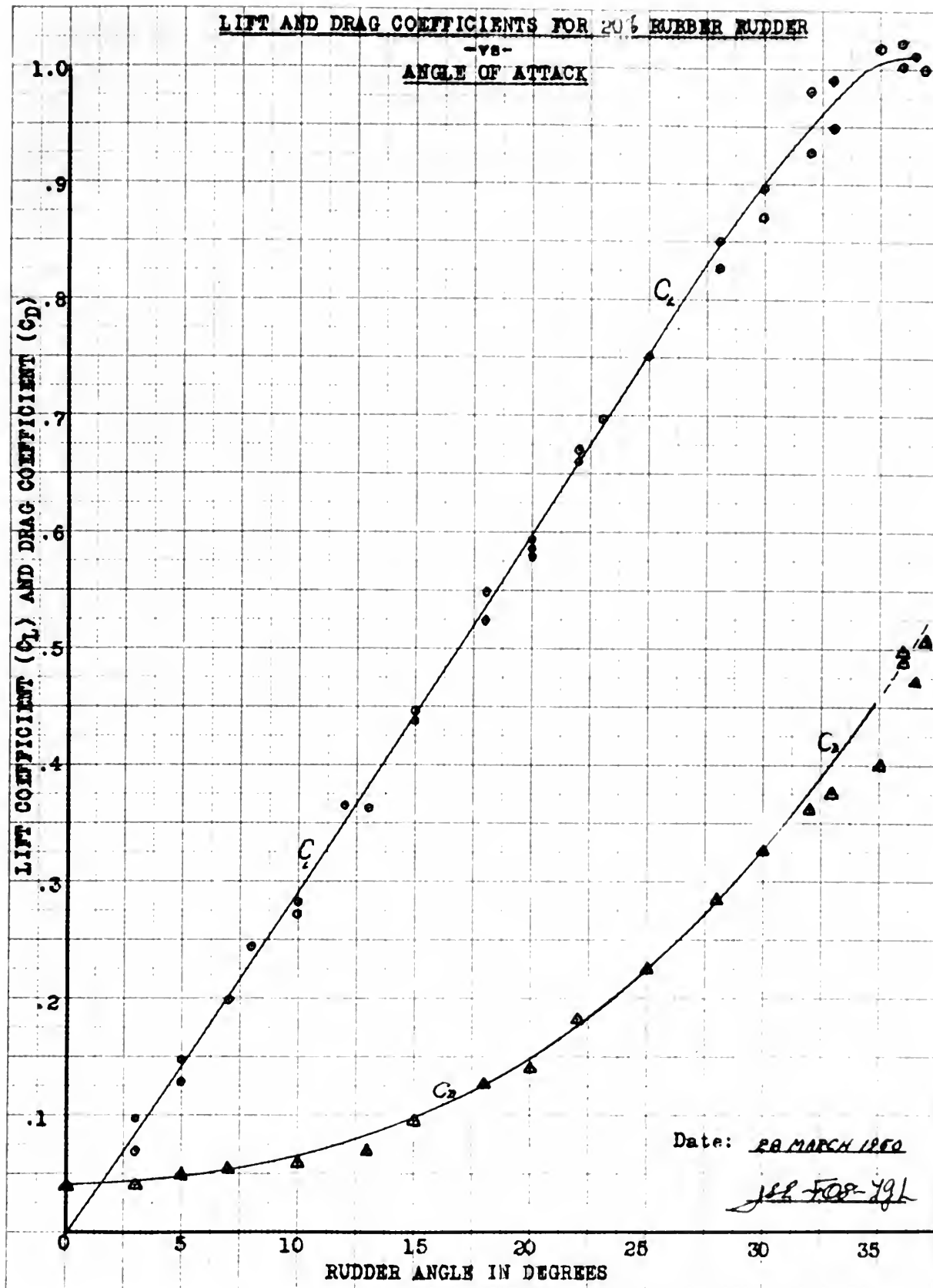






FIGURE IV

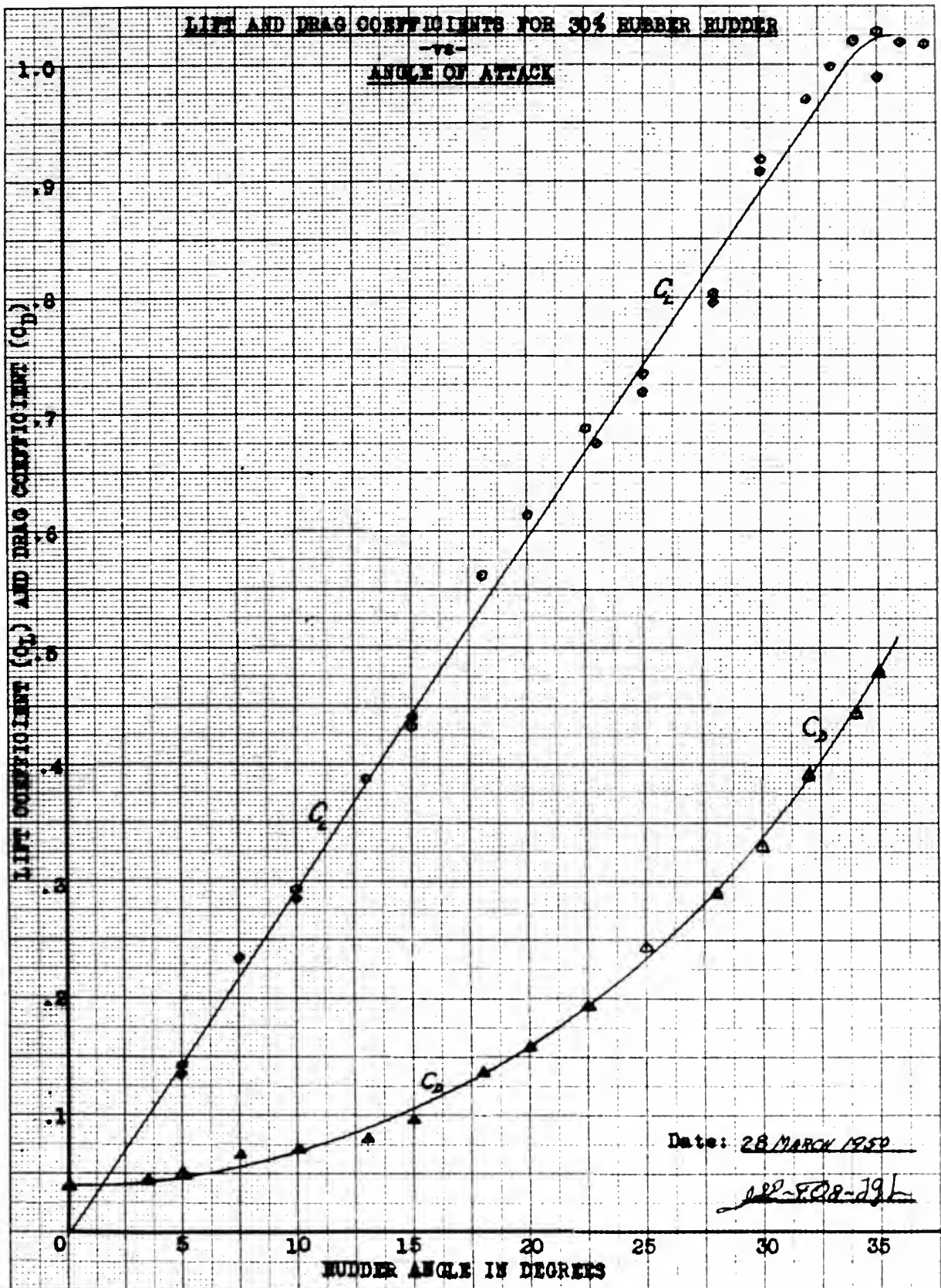




FIGURE V

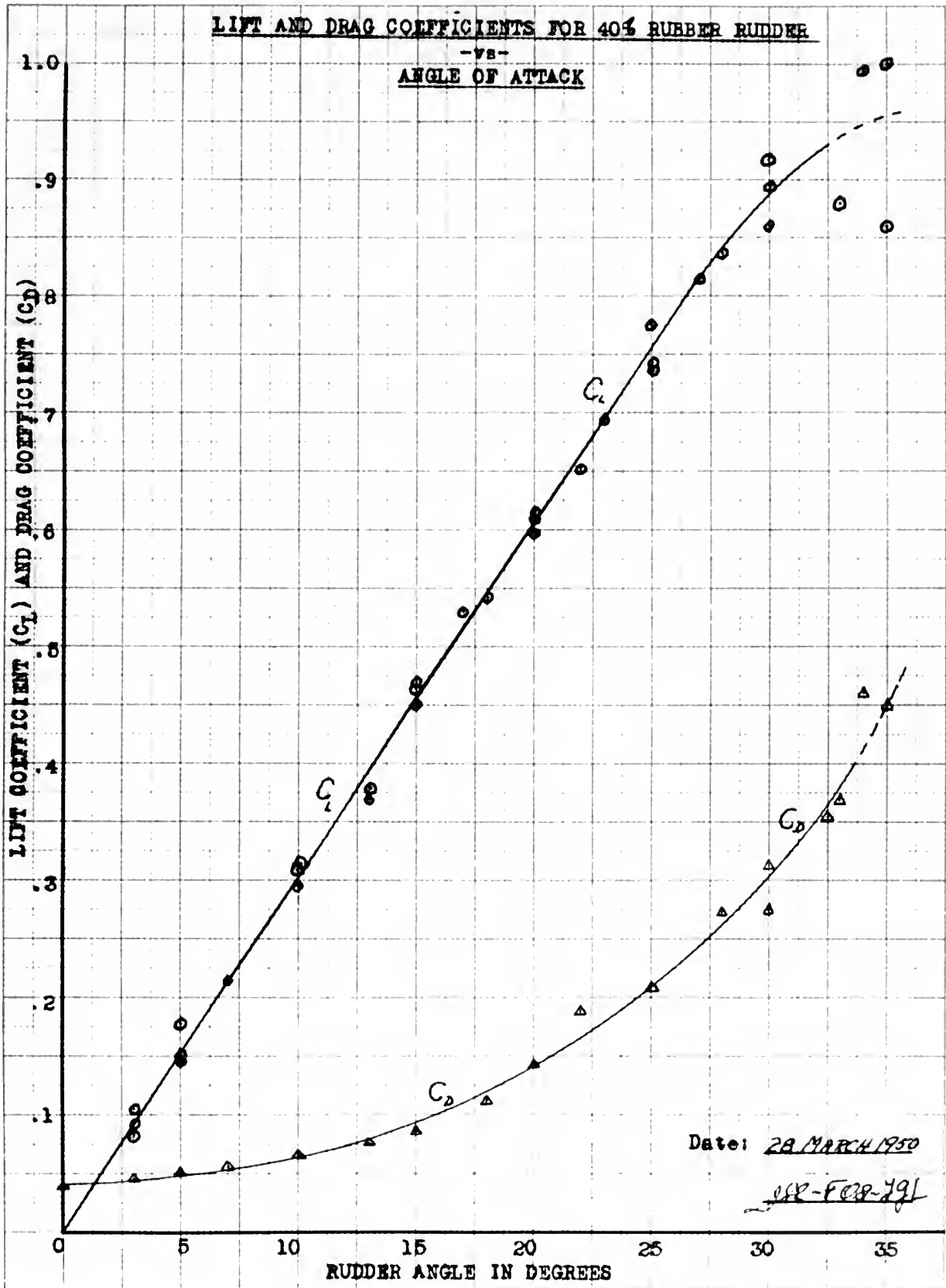




FIGURE VI

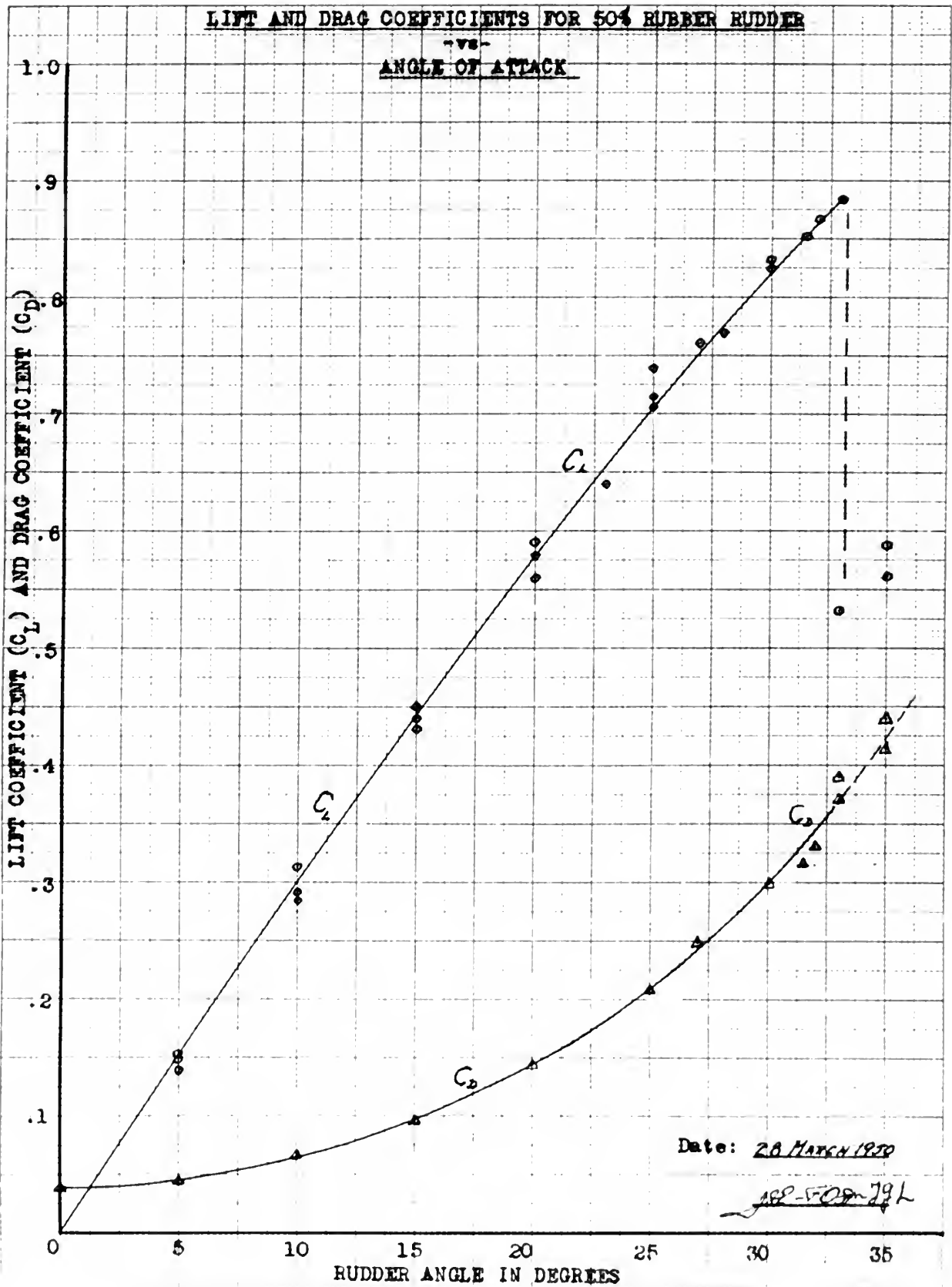




FIGURE VII

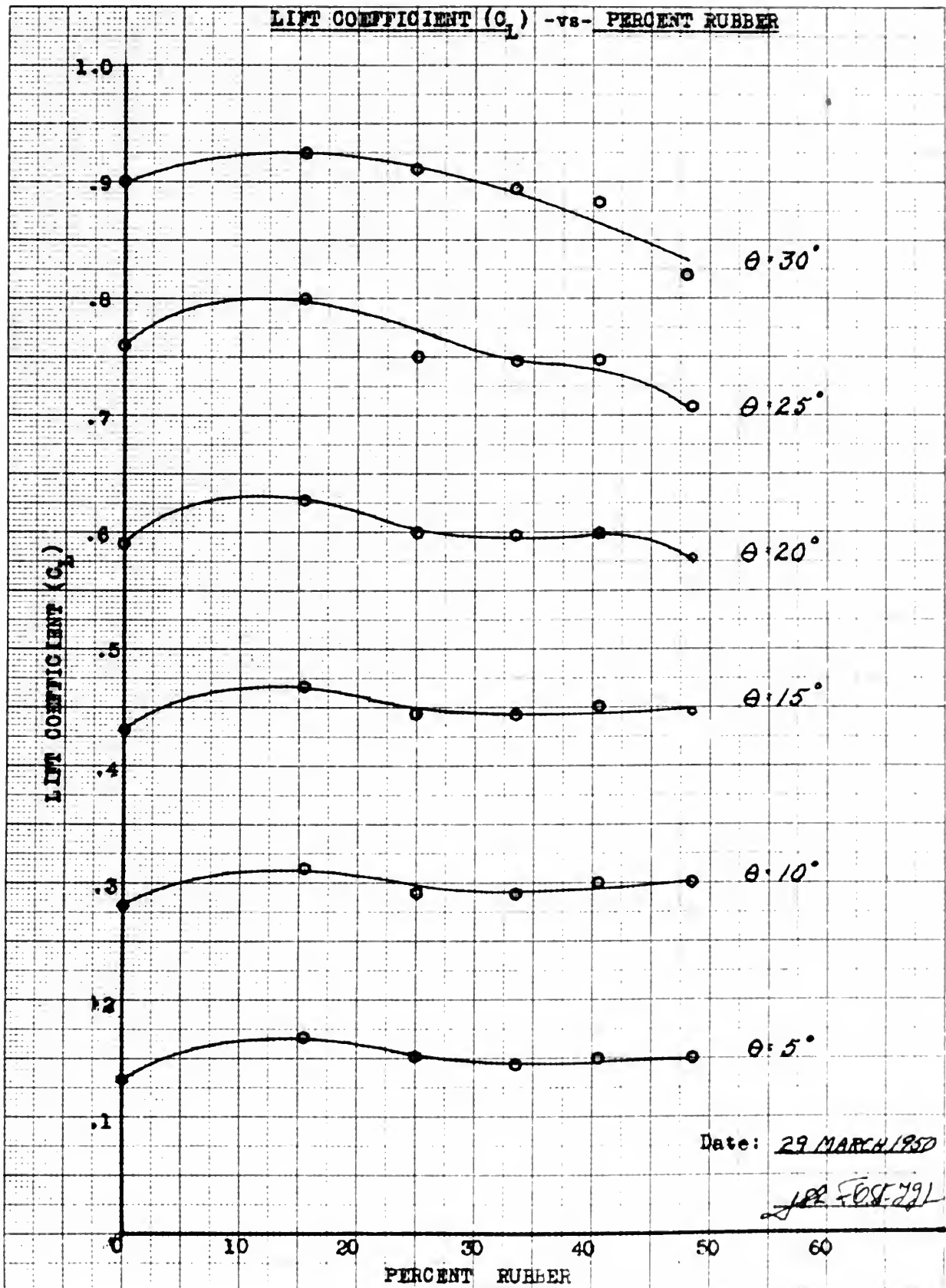
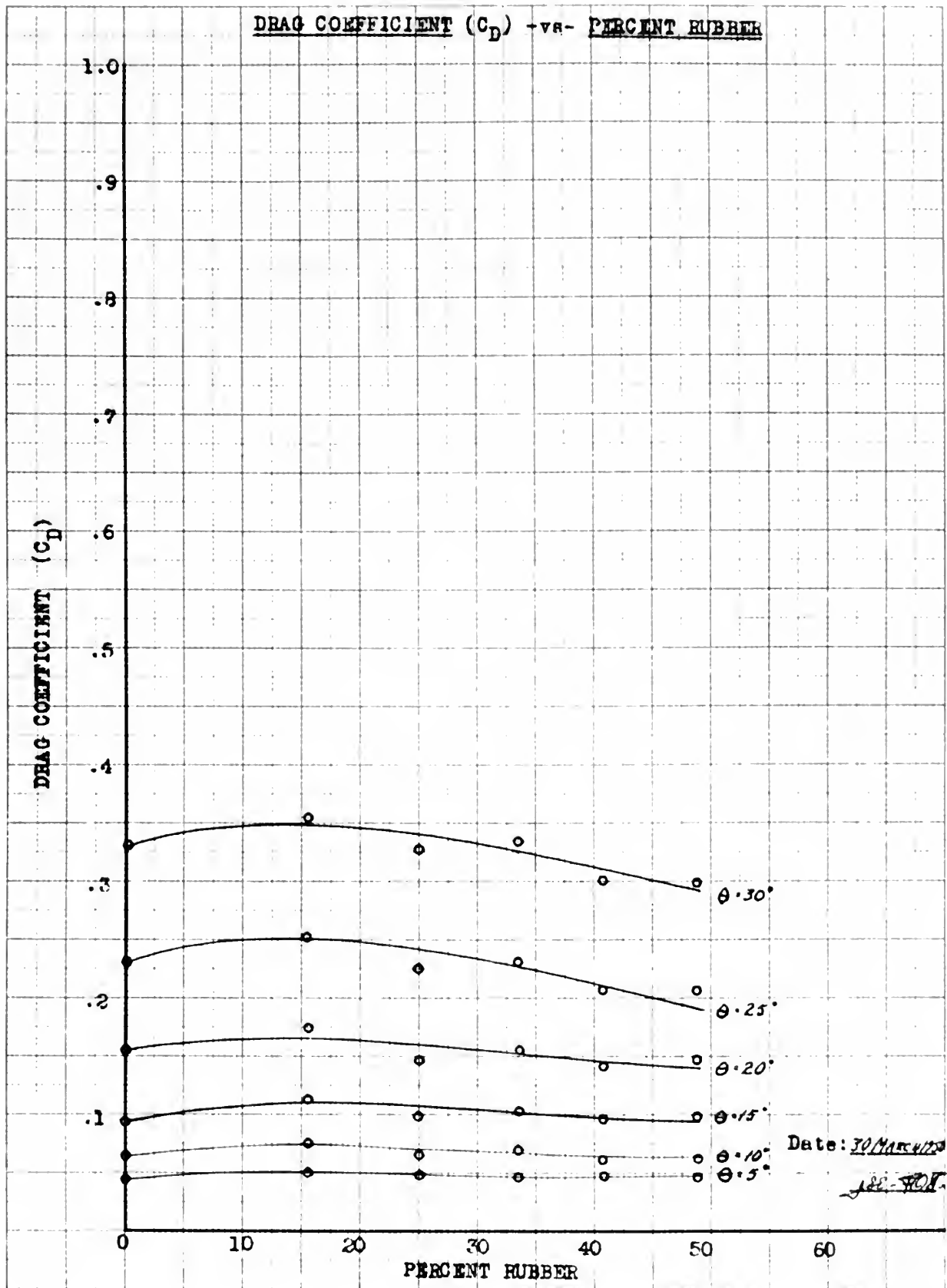






FIGURE VIII





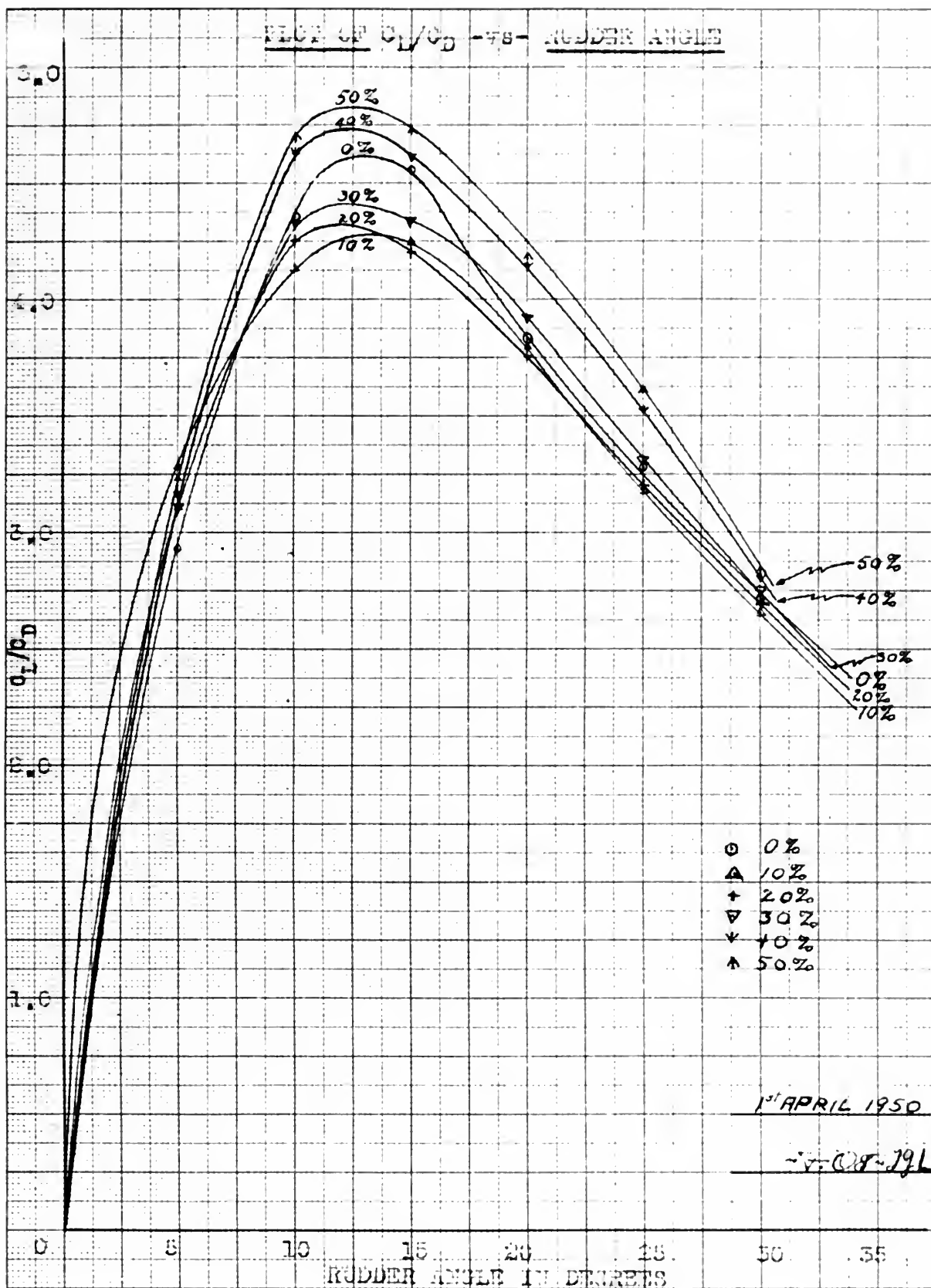
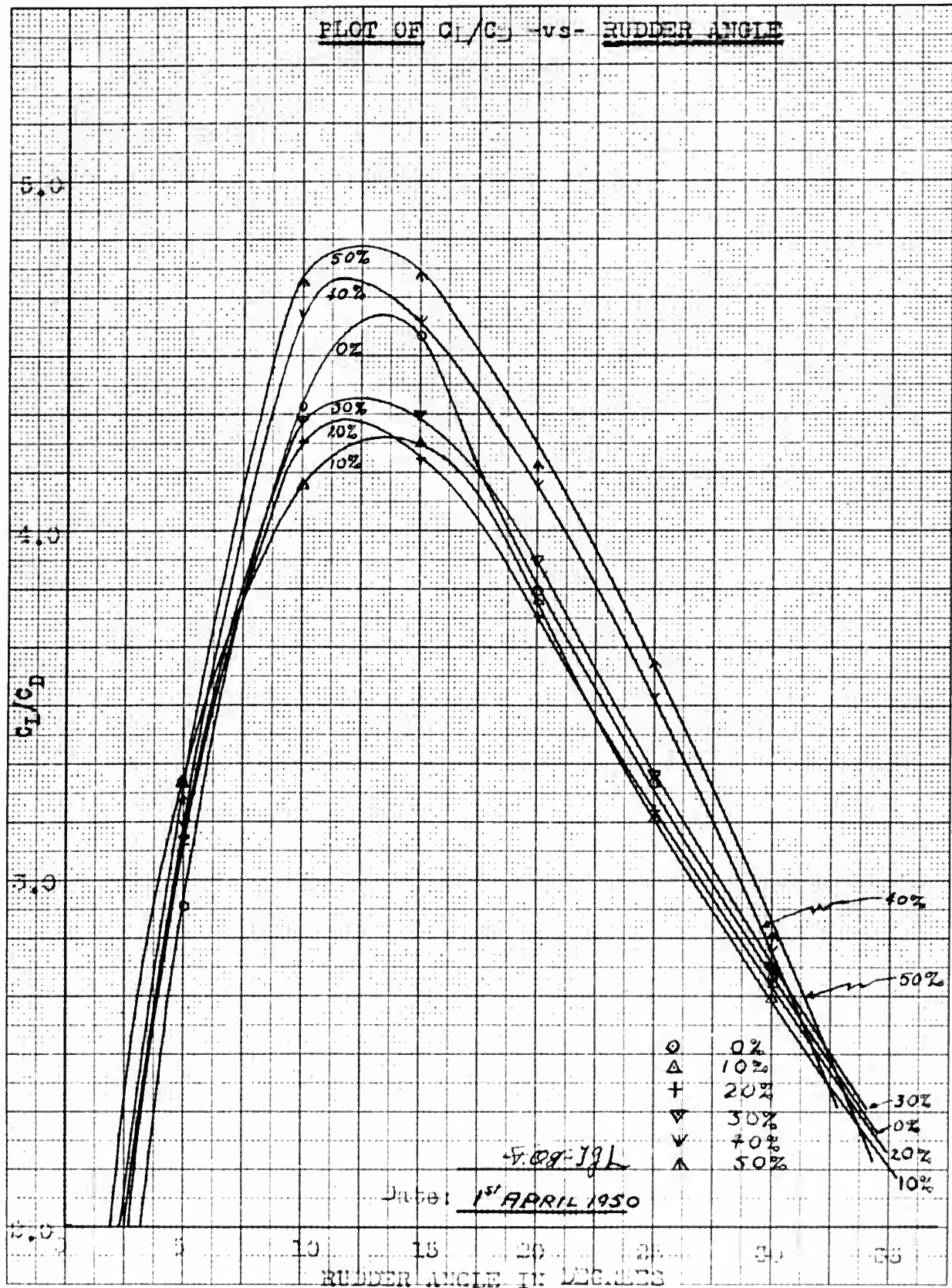




FIGURE X





## V. DISCUSSION OF RESULTS

The intention of the experiment was to determine the characteristics of rudders with 10%, 20%, 30%, 40%, and 50% rubber. However, the rudders as received from the Boston Naval Shipyard and as tested, had the following percentages of rubber:

15.4%	in lieu of	10%
25.0%	" "	20%
33.5%	" "	30%
40.7%	" "	40%
48.7%	" "	50%

There are several possible sources of error in the experimental results obtained which it is well to recognize at this time. First, while the rubber tips used on all rudders were cut from the same sheet of rubber, in an attempt to have rubber with the same characteristics on all rudders, the necessary fitting and machining of the rubber in the process of manufacturing the finished product did introduce some small differences among rubber tips. Secondly, the method of attachment of the rubber to the metal was of such a nature that the drag coefficient might be increased due to the break at the juncture (see the 50% rubber rudder of Figure 18). Thirdly, the rubber tip on the 10% rudder seems to be of a rougher surface than any of the other rubber tips, all of which had the same feel to the hand. This slightly rougher rubber surface, on the 10% rudder, may account in part for the increased drag observed with this rudder.

The rudders were balanced about the rudder stock by drilling out metal aft of the stock until a hanging balance was obtained. These holes were closed with putty prior to running tests in the tunnel, hence insuring

## V. DISCUSSION OF RESULTS

The intention of the experiment was to determine the characteristics of rubbers with 10%, 20%, 30%, 40%, and 50% rubber. However, the rubbers as received from the Boston Naval Shipyard and as tested, had the following percentages of rubber:

12.4%	in lieu of 10%
12.0%	" " " "
32.2%	" " " "
40.7%	" " " "
48.7%	" " " "

There are several possible sources of error in the experimental

results obtained which it is well to recognize at this time. First, while the rubber tips used on all rubbers were cut from the same sheet of rubber, in an attempt to have rubber with the same characteristics on all rubbers, the necessary fitting and machining of the rubber in the process of manufacturing the finished product did introduce some small differences among rubber tips. Secondly, the method of attachment of the rubber to the metal was of such a nature that the drag coefficient might be increased due to the break at the juncture (see the 50% rubber rubber of Figure 18). Thirdly, the rubber tip on the 10% rubber seems to be of a rougher surface than any of the other rubber tips, all of which had the same feel to the hand. This slightly rougher rubber surface, on the 10% rubber, may account in part for the increased drag observed with this rubber.

The rubbers were obtained about the rubber stock by drilling out metal all of the stock until a ranging balance was obtained. These holes were closed with rubber caps to prevent water in the metal, hence insuring



a smooth surface.

The metal portion of all rudders should be very nearly identical, as all were cast to the same mold. No discrepancies among the metal portions of the family of rudders was discernible.

No sources of error, other than the ever present human element, are known at this time, to exist.

From a study of figures I and VI, and observation of the tests as they were conducted, rudder breakdown seems to occur as follows:

<u>RUDDER</u>	<u>RUDDER ANGLE AT BREAKDOWN</u>
0%	30°
10%	30°
20%	32°
30%	35°
40%	32°
50%	33°

From these figures it would appear that the addition of rubber does not hasten the arrival at the breakdown angle and does have the effect of delaying this angle a few degrees.

Figure VII shows that Lift is increased by the use of rubber up to about 25% rubber at all angles of attack, but that with more than 25% of rubber the Lift falls off at angles of attack above 15°.

From Figure VIII it is seen that Drag increases with the use of rubber up to about 25% rubber and that with more than 25% rubber, the Drag decreases.

In Figures I-VI the location of 0° angle of attack was determined by measuring Lift from right rudder to left rudder and plotting the Lift against the angle of attack as indicated on the dynamometer movable head. This

a smooth surface.

The metal portion of all rubbers should be very nearly identical, as all were cast to the same mold. No discrepancies among the metal portions

of the family of rubbers was discernible.

No sources of error, other than the ever present human element, are

known at this time, to exist.

From a study of figures I and VI, and observation of the tests as they

were conducted, rubber breakdown seems to occur as follows:

RUBBER	RUBBER ANGLE AT BREAKDOWN
100	100
105	105
110	110
115	115
120	120
125	125
130	130
135	135
140	140
145	145
150	150

From these figures it would appear that the addition of rubber does not hasten the arrival at the breakdown angle and does have the effect of delaying this angle a few degrees.

Figure VII shows that life is increased by the use of rubber up to about 15% rubber at all angles of attack, but that with more than 15% of rubber the life falls at angles of attack above 15°.

From Figure VIII it is seen that life increases with the use of rubber up to about 15% rubber and that with more than 15% rubber, the life decreases.

In Figure IX, the location of the angle of attack was determined by the use of a protractor and the angle of attack was determined by the use of a protractor and the angle of attack was determined by the use of a protractor.

plot was very nearly a straight line and  $0^\circ$  angle of attack was set at the point where the plotted line crossed (zero lift) the coordinate axis showing rudder angle in degrees.

In order to produce comparative results, the drag for zero angle of attack for all rudders was corrected to the drag of the all metal rudder at zero angle of attack. For each rudder, this very small correction was applied to all values of the Drag Coefficient, thence the curves were plotted.

Beyond the point at which the rudder was believed to have reached breakdown, the Coefficient curves are dotted in, as the exact behavior of the rudder beyond this point was indeterminate.

The model Rudder Dynamometer would not give readings above 36 degrees right rudder and 10 degrees left rudder.

plot was very nearly a straight line and 90° angle of attack was set at the point where the plotted line crossed (zero lift) the coordinate axis showing rubber angle in degrees.

In order to produce comparative results, the drag for zero angle of attack for all rubbers was corrected to the drag of the all metal rubber at zero angle of attack. For each rubber, this very small correction was applied to all values of the Drag Coefficient, hence the curves were plotted. Beyond the point at which the rubber was believed to have reached breakdown, the Coefficient curves are dotted in, as the exact behavior of the rubber beyond this point was indeterminate. The model Rubber Dynamometer would not give readings above 10 degrees right rubber and 10 degrees left rubber.

## VI. CONCLUSIONS

1. With respect to the all metal rudder, the use of rubber in the construction of the rudders increased the Lift Coefficient, the maximum increase being obtained with about 12 1/2% rubber. Beyond about 25% rubber the Lift Coefficient decreases.
2. The Drag Coefficient increases up to about 25% rubber, decreasing with increase of rubber beyond 25%.
3. With respect to the all metal rudder the  $C_L/C_D$  ratio is larger for all rubber-tipped rudders at small angles of attack, below about  $8^\circ$ . This ratio is larger for the 40% rubber rudder at all angles of attack.
4. The rubber used in the experiment was too stiff for best performance.

CONCLUSIONS

1. With respect to the all metal rubber, the use of rubber in the construction of the rubber increased the Lift Coefficient, the maximum increase being obtained with about 15% rubber. Beyond about 15% rubber the Lift Coefficient decreases.
2. The Drag Coefficient increases up to about 15% rubber, decreasing with increase of rubber beyond 15%.
3. With respect to the all metal rubber the  $C_L/C_D$  ratio is larger for all rubber-tipped rubbers at small angles of attack, below about 6°. This ratio is larger for the 45% rubber rubber at all angles of attack.
4. The rubber used in the experiment was too stiff for best performance.

## VII. RECOMMENDATIONS

1. That further experimental work be done with semi-flexible rubbers along the following lines:
  - a) Utilize rubber of varying degrees of stiffness.
  - b) Conduct a close search of the area within the 5% to 15% rubber zone.
  - c) Conduct experiments with all rubber rudders in which the forward portion (percentage determined by previous work), of the rudder is stiffened by internal framework so that it is inflexible and the after portion free to flex. Use of such a rudder would exclude the possibility of erroneous results such as increased drag due to the break at the junction of the rubber and metal.
2. That the possibility of using a flexible trailing edge on propellers be investigated.
3. That the effects of the ship's hull and the propellers race on the rubber-tipped rudders be investigated.

## VII. RECOMMENDATIONS

1. That further experimental work be done with semi-flexible rubbers along

the following lines:

a) Define rubber of varying degrees of stiffness.

b) Conduct a close search of the area within the 5% to 15%

rubber zone.

c) Conduct experiments with all rubber rubbers in which the

forward portion (percentage determined by previous work)

of the rubber is stiffened by internal framework so that it is

inelastic and the other portion free to flex. Use of such a

rubber would exclude the possibility of erroneous results

such as increased drag due to the break at the junction of the

rubber and metal.

2. That the possibility of using a flexible trailing edge on propellers be

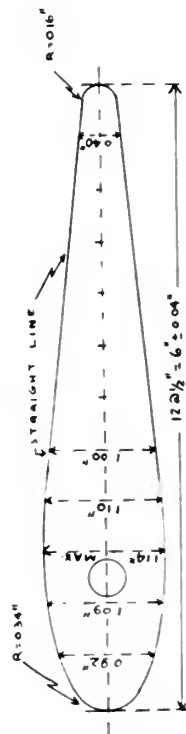
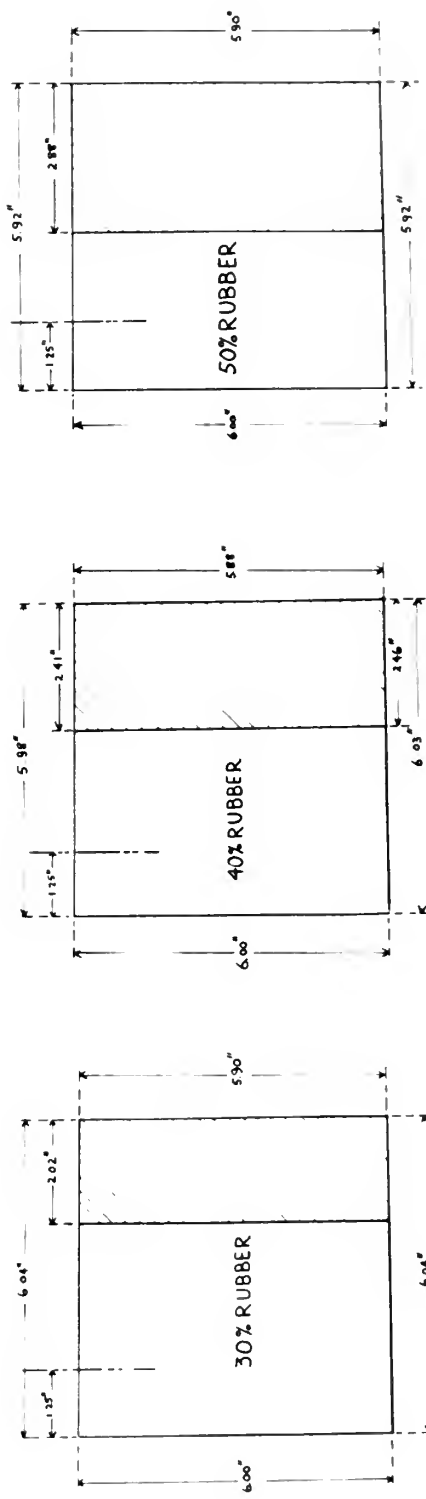
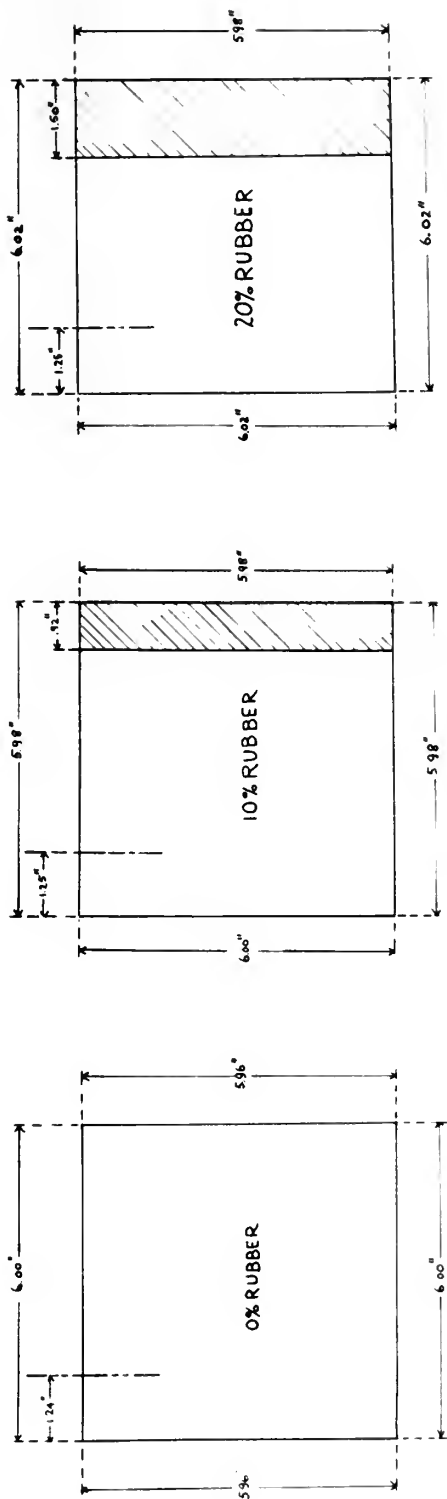
investigated.

3. That the effects of the ship's hull and the propellers race on the rubber-

tipped rubbers be investigated.



FIGURE XI



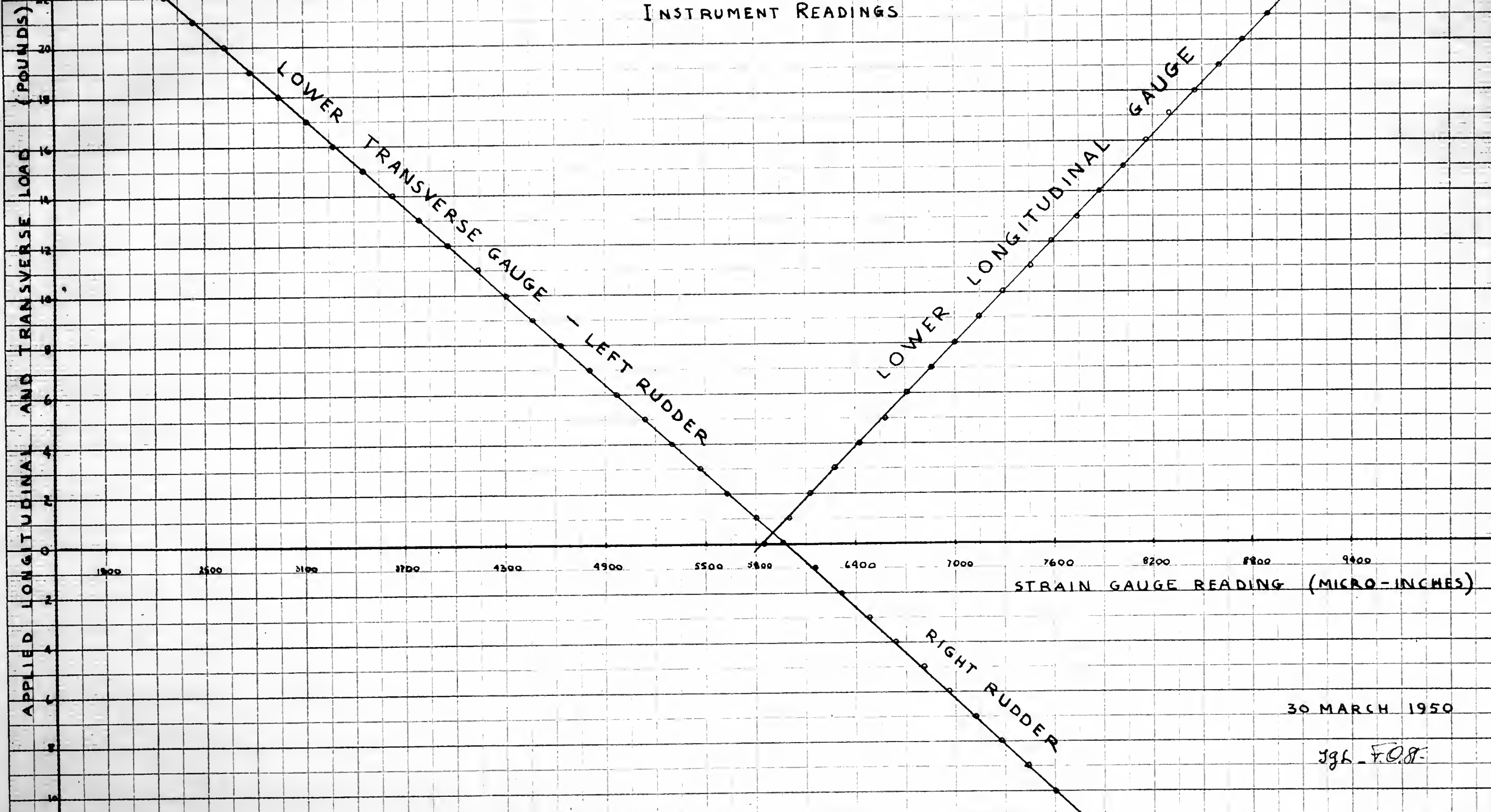
29 MARCH 1950  
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FIGURE XII

CALIBRATION CURVES FOR RUDDER DYNAMOMETER

APPLIED LOADS  
VS  
INSTRUMENT READINGS



30 MARCH 1950

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**FIG. XIII - INSTRUMENTS**





FIG XIV- INSTRUMENTS AND  
DYNAMOMETER  
28





FIG XV — MODEL RUDDERS





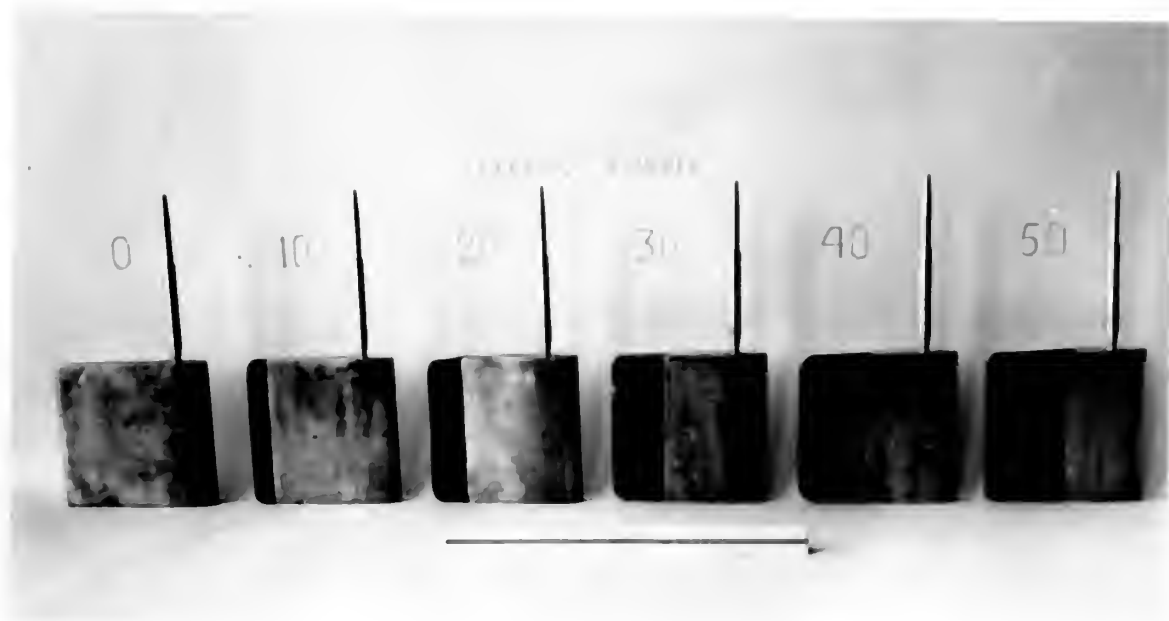


FIG XVI - ELEVATION AND PLAN VIEW OF MODEL RUDDERS





40%

FIG XVII- 40% RUBBER RUDDER





FIG XVIII - RUDDER BEING BENT





FIG XIX - CALIBRATION SET-UP





VIII. APPENDIX

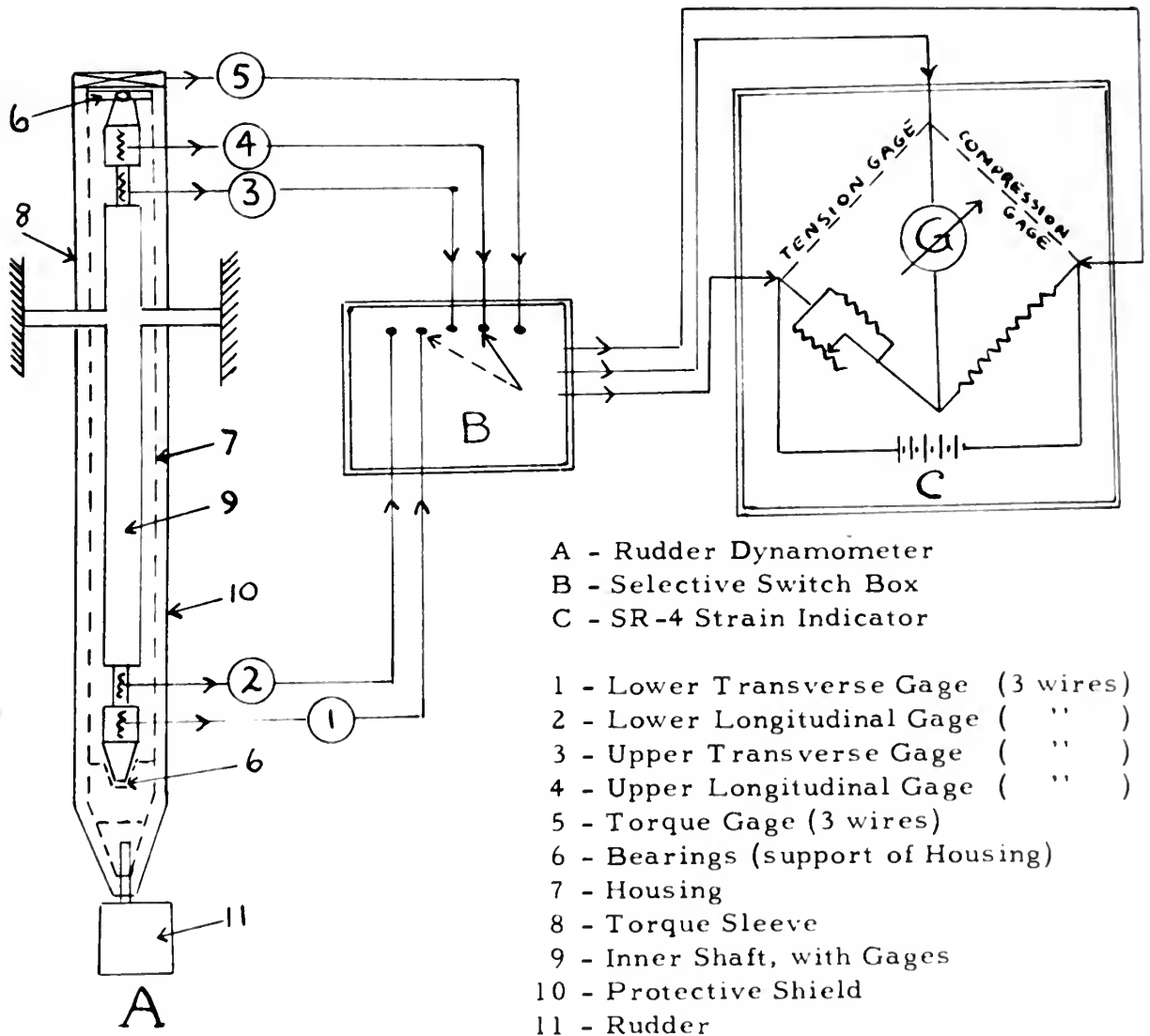
APPENDIX "A"

VIII. APPENDIX

APPENDIX "A"

## THE M. I. T. MODEL RUDDER DYNAMOMETER

The measurement of Lift and Drag forces for the development of this thesis was made with the Model Dynamometer designed by Kissinger and Rupp (11). A sketch of the Dynamometer's essential details and a brief explanation of its operation follows:



NOTE: Resistors shown dotted in the Wheatstone Bridge are the pair of gages (tension & compression) in use; they actually are mounted on the dynamometer.



The Model Dynamometer consists of a steel shaft (9) carrying two sets of strain gages (1, 2, 3, 4) and rigidly supported by a casting, which is the only outside support. The four strain gages are mounted in two mutually perpendicular reduced sections at the upper and lower end of the shaft, i.e., parallel and normal to the water flow. The shaft is enclosed by a watertight cylinder (7) which is supported at both ends of the shaft (9). The rudder stock is firmly held by this cylinder, thus transmitting all forces to the inner shaft.

Above the dynamometer support a sleeve (6) is mounted around the cylinder; the torque gage is installed between this sleeve and the cylinder (7). This gage will not be discussed here as it was not used during the experiments.

Below the Dynamometer support there is a protective shield (10) with the lower end tapered. To avoid corrections for drag forces this tapered end was brought very close to the upper surface of the rudder.

The strain gages consist of fine wires cemented to the reduced sections in the direction of the pure bending introduced by either longitudinal or transverse forces. Three electrical leads are used with each strain gage, namely - tension side, compression side and neutral axis (common ground). The leads from all gages were connected to a selective switch box which in turn was connected to the SR-4 Strain Indicator. This indicator consists of a built-in Wheatstone bridge with galvanometer for obtaining balance among the resistances. A high sensitivity, as well as temperature correction, was obtained by connecting simultaneously the tension and compression leads from the gage in use to the SR-4 Indicator.

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Above the dynamometer support a sleeve (8) is mounted around the cylinder; the torque gage is installed between this sleeve and the cylinder (7). This gage will not be discussed here as it was not used during the experiments.

Below the Dynamometer support there is a protective shield (10) with the lower end tapered. To avoid corrections for drag forces this tapered end was brought very close to the upper surface of the rubber.

The strain gages consist of fine wires cemented to the reduced sections in the direction of the pure bending introduced by either longitudinal or transverse forces. Three electrical leads are used with each strain gage, namely - tension side, compression side and neutral axis (common ground). The leads from all gages were connected to a selective switch box which in turn was connected to the S-R-4 Strain Indicator. This indicator consists of a built-in Wheatstone bridge with galvanometer for obtaining balance among the resistances. A high sensitivity, as well as temperature correction, was obtained by connecting simultaneously the tension and compression leads from the gage in use to the S-R-4 indicator.

Due to changes made in the Dynamometer it was decided to use only the two lower strain gages, the location of the upper gages making their readings less sensitive than the lower. During calibration of the Lower Longitudinal Gage, care was taken to insure that only longitudinal forces would act on the Dynamometer (by keeping zero reading on the Transverse Gage). Therefore, the SR-4 Indicator reading for a given longitudinal force was always the same, regardless of the readings of the upper gages. The same applies to the Lower Transverse Gage.

This procedure simplifies the use of the Rudder Dynamometer as it does not require the resolution of the applied load into its upper and lower components, as was required in the original design.

The use of the SR-4 Strain Indicator together with the selective switch simplified considerably the test procedure.

For a detailed explanation of the Rudder Dynamometer the reader is referred to reference (11) in the bibliography.



Due to changes made in the Dynamometer it was decided to use only the two lower strain gages, the location of the upper gages making their readings less sensitive than the lower. During calibration of the lower longitudinal Gage care was taken to insure that only longitudinal forces would act on the Dynamometer (by keeping zero reading on the Transverse Gage). Therefore, the 2X-4 indicator reading for a given longitudinal force was always the same, regardless of the readings of the upper gages. The same applies to the lower Transverse Gage.

This procedure simplified the use of the Rubber Dynamometer as it does not require the resolution of the applied load into its upper and lower components, as was required in the original design. The use of the 2X-4 strain indicator together with the selective switch simplified considerably the test procedure. For a detailed explanation of the Rubber Dynamometer the reader is referred to reference (1) in the bibliography.

APPENDIX "B"

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# CALIBRATION DATA

(Ahead motion)

Date: 2/24/1950

## Gauge Lower Transverse (LT)

## Gauge Lower Longitudinal (LL)

Applied Load      Strain reading  
                         (micro-inches)

Applied Load      Strain reading  
                         (micro-inches)

### Left rudder

-----

0#	5960
1	3800
2	5630
3	5470
4	5300
5	5140
6	4970
7	4810
8	4640
9	4470
10	4310
11	4140
12	3960
13	3790
14	3630
15	3460
16	3280
17	3115
18	2950
19	2780
20	2620
21	2430
22	2270
23	2100
24	1930
25	1780

0#	5850
1	6000
2	6130
3	6260
4	6430
5	6580
6	6715
7	6860
8	7000
9	7145
10	7290
11	7430
12	7585
13	7740
14	7875
15	8020
16	8160
17	8300
18	8450
19	8600
20	8745
21	8900
22	9045
23	9190
24	9340
25	9490
26	9630

### Right Rudder

1	6150
2	6310
3	6480
4	6640
5	6810
6	6960
7	7120
8	7280
9	7440
10	7610

# CALIBRATION DATA

Date: 5/14/1950

(Ahead motion)

Gauge Lower Longitudinal (L.L.)

Gauge Lower Transverse (L.T.)

Applied Load	Strain reading (micro-inches)	Applied Load	Strain reading (micro-inches)
0	2820	0	2960
1	6000	1	2800
2	6130	2	2630
3	6280	3	2470
4	6430	4	2300
5	6580	5	2140
6	6712	6	1970
7	6860	7	1810
8	7000	8	1640
9	7142	9	1470
10	7290	10	1310
11	7430	11	1140
12	7582	12	960
13	7740	13	790
14	7872	14	620
15	8020	15	450
16	8160	16	280
17	8300	17	112
18	8450	18	20
19	8600	19	2780
20	8742	20	2620
21	8900	21	2430
22	9042	22	2270
23	9190	23	2100
24	9340	24	1920
25	9480	25	1760
26	9630		

Right Rudder

1	6130
2	6310
3	6480
4	6640
5	6810
6	6900
7	7120
8	7380
9	7600
10	7810

The calibration curves (Figure XII) were plotted after obtaining the data from the preceding page and were used throughout the tests, checks being made after each series of runs.

The calibration curves (Figure XII) were plotted after obtaining the data

from the preceding page and were used throughout the tests, checks being

made after each series of runs.

Temperature, °C.	Time, min.	Pressure, mm. Hg.	Flow, cc./min.	Viscosity, poise
100	10	100	1.0	0.01
100	20	100	1.0	0.01
100	30	100	1.0	0.01
100	40	100	1.0	0.01
100	50	100	1.0	0.01
100	60	100	1.0	0.01
100	70	100	1.0	0.01
100	80	100	1.0	0.01
100	90	100	1.0	0.01
100	100	100	1.0	0.01
100	110	100	1.0	0.01
100	120	100	1.0	0.01
100	130	100	1.0	0.01
100	140	100	1.0	0.01
100	150	100	1.0	0.01
100	160	100	1.0	0.01
100	170	100	1.0	0.01
100	180	100	1.0	0.01
100	190	100	1.0	0.01
100	200	100	1.0	0.01
100	210	100	1.0	0.01
100	220	100	1.0	0.01
100	230	100	1.0	0.01
100	240	100	1.0	0.01
100	250	100	1.0	0.01
100	260	100	1.0	0.01
100	270	100	1.0	0.01
100	280	100	1.0	0.01
100	290	100	1.0	0.01
100	300	100	1.0	0.01
100	310	100	1.0	0.01
100	320	100	1.0	0.01
100	330	100	1.0	0.01
100	340	100	1.0	0.01
100	350	100	1.0	0.01
100	360	100	1.0	0.01
100	370	100	1.0	0.01
100	380	100	1.0	0.01
100	390	100	1.0	0.01
100	400	100	1.0	0.01
100	410	100	1.0	0.01
100	420	100	1.0	0.01
100	430	100	1.0	0.01
100	440	100	1.0	0.01
100	450	100	1.0	0.01
100	460	100	1.0	0.01
100	470	100	1.0	0.01
100	480	100	1.0	0.01
100	490	100	1.0	0.01
100	500	100	1.0	0.01
100	510	100	1.0	0.01
100	520	100	1.0	0.01
100	530	100	1.0	0.01
100	540	100	1.0	0.01
100	550	100	1.0	0.01
100	560	100	1.0	0.01
100	570	100	1.0	0.01
100	580	100	1.0	0.01
100	590	100	1.0	0.01
100	600	100	1.0	0.01
100	610	100	1.0	0.01
100	620	100	1.0	0.01
100	630	100	1.0	0.01
100	640	100	1.0	0.01
100	650	100	1.0	0.01
100	660	100	1.0	0.01
100	670	100	1.0	0.01
100	680	100	1.0	0.01
100	690	100	1.0	0.01
100	700	100	1.0	0.01
100	710	100	1.0	0.01
100	720	100	1.0	0.01
100	730	100	1.0	0.01
100	740	100	1.0	0.01
100	750	100	1.0	0.01
100	760	100	1.0	0.01
100	770	100	1.0	0.01
100	780	100	1.0	0.01
100	790	100	1.0	0.01
100	800	100	1.0	0.01
100	810	100	1.0	0.01
100	820	100	1.0	0.01
100	830	100	1.0	0.01
100	840	100	1.0	0.01
100	850	100	1.0	0.01
100	860	100	1.0	0.01
100	870	100	1.0	0.01
100	880	100	1.0	0.01
100	890	100	1.0	0.01
100	900	100	1.0	0.01
100	910	100	1.0	0.01
100	920	100	1.0	0.01
100	930	100	1.0	0.01
100	940	100	1.0	0.01
100	950	100	1.0	0.01
100	960	100	1.0	0.01
100	970	100	1.0	0.01
100	980	100	1.0	0.01
100	990	100	1.0	0.01
100	1000	100	1.0	0.01

# SAMPLE LIFT COEFFICIENTS USED ON PLOTS\*

Rudder Angle	Rudder 0%	Rudder 10%	Rudder 20%	Rudder 30%	Rudder 40%	Rudder 50%
0°	0.0	0.0	0.0	0.0	0.0	0.0
3	.069	.127	.097		.092	
5	.132	.175	.147	.143	.150	.153
7	.175	.225	.200	.234	.215	
10	.279	.309	.283	.292	.310	.313
13	.360	.393	.362	.387	.378	
15	.429	.475	.446	.441	.465	.450
18	.525	.570	.550	.562	.542	
20	.585	.630	.587	.614	.608	.580
22	.644	.705	.671	.688	.654	
25	.760	.790	.752	.735	.743	.715
28	.847		.850	.804	.837	.770
30	.894	.927	.897	.908	.894	.825
32	.955	.630	.980	.970		.868
33	.953	.605	.991	.998	.880	.532
34	.960			1.021	.994	
35		.715	1.018	1.028	.860	.561

\* The above tabulation refers to one series of runs only.

The curves of Figures I to VI were plotted with data of five complete series of runs.



# THE COMPOSITE FIRST COEFFICIENTS USED ON PLOTS

Angle	Rubber 10%	Rubber 20%	Rubber 30%	Rubber 40%	Rubber 50%
0°	0.0	0.0	0.0	0.0	0.0
1	0.00	0.01	0.02	0.03	0.04
2	0.01	0.02	0.03	0.04	0.05
3	0.02	0.03	0.04	0.05	0.06
4	0.03	0.04	0.05	0.06	0.07
5	0.04	0.05	0.06	0.07	0.08
6	0.05	0.06	0.07	0.08	0.09
7	0.06	0.07	0.08	0.09	0.10
8	0.07	0.08	0.09	0.10	0.11
9	0.08	0.09	0.10	0.11	0.12
10	0.09	0.10	0.11	0.12	0.13
11	0.10	0.11	0.12	0.13	0.14
12	0.11	0.12	0.13	0.14	0.15
13	0.12	0.13	0.14	0.15	0.16
14	0.13	0.14	0.15	0.16	0.17
15	0.14	0.15	0.16	0.17	0.18
16	0.15	0.16	0.17	0.18	0.19
17	0.16	0.17	0.18	0.19	0.20
18	0.17	0.18	0.19	0.20	0.21
19	0.18	0.19	0.20	0.21	0.22
20	0.19	0.20	0.21	0.22	0.23
21	0.20	0.21	0.22	0.23	0.24
22	0.21	0.22	0.23	0.24	0.25
23	0.22	0.23	0.24	0.25	0.26
24	0.23	0.24	0.25	0.26	0.27
25	0.24	0.25	0.26	0.27	0.28
26	0.25	0.26	0.27	0.28	0.29
27	0.26	0.27	0.28	0.29	0.30
28	0.27	0.28	0.29	0.30	0.31
29	0.28	0.29	0.30	0.31	0.32
30	0.29	0.30	0.31	0.32	0.33
31	0.30	0.31	0.32	0.33	0.34
32	0.31	0.32	0.33	0.34	0.35
33	0.32	0.33	0.34	0.35	0.36
34	0.33	0.34	0.35	0.36	0.37
35	0.34	0.35	0.36	0.37	0.38

The above tabulation refers to one series of runs only.

The curves in Figures I to VI were plotted with data of five complete

series of runs.

# SAMPLE DRAG COEFFICIENTS USED ON PLOTS\*

Rudder Angle	Rudder 0%	Rudder 10%	Rudder 20%	Rudder 30%	Rudder 40%	Rudder 50%
0°	.040	.040	.040	.040	.040	.040
3	.041	.046	.040	.044	.046	. -
5	.046	.051	.050	.050	.051	.045
7	.056	.061	.055	.066	.056	. -
10	.066	.077	.060	.071	.066	.066
13	.071	.102	.071	.081	.076	. -
15	.097	.117	.096	.096	.087	.096
18	.123	.148	.127	.137	.112	. -
20	.153	.194	.142	.158	.143	.142
22	.184	.214	.183	.192	.188	. -
25	.230	.250	.224	.244	.209	.209
28	.301	.327	.285	.290	.273	. -
30	.332	.352	.326	.331	.313	.300
32	.383	.357	.362	.392	.355	.331
33	.408	.455	.377	. -	.369	.392
34	.440	. -	. -	.444	.461	. -
35	.460	.485	.400	.479	.450	.439

(\*) The above tabulation refers to one series of runs only; the data was corrected for drag at zero rudder angle to be equal for all rudders.

The curves (Figures I to VI) were plotted with data of five complete series of runs.

# SAMPLE BRAG COEFFICIENTS USED ON PLOTS

Angle	0°	10°	20°	30°	40°	50°
0°	.040	.040	.040	.040	.040	.040
2	.041	.040	.040	.040	.040	.040
4	.040	.039	.039	.039	.039	.039
7	.039	.038	.038	.038	.038	.038
10	.038	.037	.037	.037	.037	.037
12	.037	.036	.036	.036	.036	.036
15	.037	.035	.035	.035	.035	.035
18	.036	.034	.034	.034	.034	.034
20	.036	.033	.033	.033	.033	.033
22	.035	.032	.032	.032	.032	.032
25	.033	.030	.030	.030	.030	.030
28	.031	.027	.027	.027	.027	.027
30	.030	.026	.026	.026	.026	.026
32	.028	.024	.024	.024	.024	.024
33	.028	.023	.023	.023	.023	.023
34	.028	.022	.022	.022	.022	.022
35	.028	.022	.022	.022	.022	.022

(\*) The above tabulation refers to one series of runs only; the data was

corrected for drag at zero rudder angle to be equal for all rudders.

The curves (Figures I to VI) were plotted with data of five complete

series of runs.

# DATA FOR CURVES ON FIGURES IX and X

## LIFT COEFFICIENT $C_L$ - vs - RUBBER PERCENTAGE\*

ANGLE	PERCENTAGE OF RUBBER					
	0%	10%	20%	30%	40%	50%
5°	.132	.167	.152	.146	.148	.152
10°	.283	.310	.298	.293	.295	.302
15°	.433	.467	.450	.445	.445	.450
20°	.593	.628	.602	.595	.599	.580
25°	.760	.797	.775	.748	.739	.701
30°	.898	.925	.915	.890	.865	.833

## DRAW COEFFICIENT $C_D$ - vs - RUBBER PERCENTAGE\*

ANGLE	PERCENTAGE OF RUBBER					
	0%	10%	20%	30%	40%	50%
5°	.045	.051	.049	.047	.047	.047
10°	.065	.075	.070	.068	.064	.064
15°	.095	.110	.107	.103	.097	.095
20°	.155	.165	.160	.152	.145	.138
25°	.232	.251	.242	.226	.210	.193
30°	.330	.348	.340	.325	.310	.292

## $C_L/C_D$ - vs - RUBBER PERCENTAGE

ANGLE	PERCENTAGE OF RUBBER					
	0%	10%	20%	30%	40%	50%
5°	2.93	3.28	3.10	3.11	3.15	3.24
10°	4.36	4.13	4.26	4.32	4.62	4.72
15°	4.56	4.25	4.21	4.33	4.59	4.74
20°	3.83	3.80	3.76	3.92	4.13	4.20
25°	3.28	3.18	3.20	3.31	3.52	3.63
30°	2.72	2.66	2.69	2.74	2.79	2.85

\*NOTE: These values were taken from faired curves on Figures VII and VIII.

# DATA FOR CURVES ON FIGURES IX and X

LIST COEFFICIENT C<sub>L</sub> - RUBBER PERCENTAGE

ANGLE	0%	10%	20%	30%	40%	50%
30°	0.04	0.05	0.06	0.07	0.08	0.09
35°	0.05	0.06	0.07	0.08	0.09	0.10
40°	0.06	0.07	0.08	0.09	0.10	0.11
45°	0.07	0.08	0.09	0.10	0.11	0.12
50°	0.08	0.09	0.10	0.11	0.12	0.13
55°	0.09	0.10	0.11	0.12	0.13	0.14
60°	0.10	0.11	0.12	0.13	0.14	0.15
65°	0.11	0.12	0.13	0.14	0.15	0.16
70°	0.12	0.13	0.14	0.15	0.16	0.17
75°	0.13	0.14	0.15	0.16	0.17	0.18
80°	0.14	0.15	0.16	0.17	0.18	0.19
85°	0.15	0.16	0.17	0.18	0.19	0.20
90°	0.16	0.17	0.18	0.19	0.20	0.21

DRAG COEFFICIENT C<sub>D</sub> - RUBBER PERCENTAGE

ANGLE	0%	10%	20%	30%	40%	50%
30°	0.00	0.00	0.00	0.00	0.00	0.00
35°	0.00	0.00	0.00	0.00	0.00	0.00
40°	0.00	0.00	0.00	0.00	0.00	0.00
45°	0.00	0.00	0.00	0.00	0.00	0.00
50°	0.00	0.00	0.00	0.00	0.00	0.00
55°	0.00	0.00	0.00	0.00	0.00	0.00
60°	0.00	0.00	0.00	0.00	0.00	0.00
65°	0.00	0.00	0.00	0.00	0.00	0.00
70°	0.00	0.00	0.00	0.00	0.00	0.00
75°	0.00	0.00	0.00	0.00	0.00	0.00
80°	0.00	0.00	0.00	0.00	0.00	0.00
85°	0.00	0.00	0.00	0.00	0.00	0.00
90°	0.00	0.00	0.00	0.00	0.00	0.00

C<sub>L</sub>/C<sub>D</sub> - RUBBER PERCENTAGE

ANGLE	0%	10%	20%	30%	40%	50%
30°	0.00	0.00	0.00	0.00	0.00	0.00
35°	0.00	0.00	0.00	0.00	0.00	0.00
40°	0.00	0.00	0.00	0.00	0.00	0.00
45°	0.00	0.00	0.00	0.00	0.00	0.00
50°	0.00	0.00	0.00	0.00	0.00	0.00
55°	0.00	0.00	0.00	0.00	0.00	0.00
60°	0.00	0.00	0.00	0.00	0.00	0.00
65°	0.00	0.00	0.00	0.00	0.00	0.00
70°	0.00	0.00	0.00	0.00	0.00	0.00
75°	0.00	0.00	0.00	0.00	0.00	0.00
80°	0.00	0.00	0.00	0.00	0.00	0.00
85°	0.00	0.00	0.00	0.00	0.00	0.00
90°	0.00	0.00	0.00	0.00	0.00	0.00

These values were taken from the curves on Figures VII and VIII.

**APPENDIX "C"**

APPENDIX "C"

# TYPICAL DATA SHEET

Rudder: 0% rubber

Water temperature: 62°F - Water speed: 9 ft/sec. - Date: 3/24/50

Rudder Angle (right)	Gauge LT Reading	Lift Force	$C_L$	Gauge LL Reading	Drag Force	$C_D$
0°	5960	0.0	0.000	5960	0.8	.041
3	5725	1.4	.071	5960	0.8	.041
5	5580	2.3	.117	5970	0.9	.046
7	5380	3.5	.179	5980	1.1	.056
10	5035	5.6	.286	6030	1.3	.066
13	4770	7.1	.362	6050	1.4	.071
15	4530	8.6	.440	6110	1.9	.097
18	4250	10.3	.526	6180	2.4	.123
20	4010	11.7	.596	6260	3.0	.153
22	3750	13.2	.675	6360	3.6	.184
25	3450	15.0	.766	6490	4.5	.230
28	3180	16.6	.848	6670	5.9	.301
30	3030	17.5	.895	6780	6.5	.332
32	2830	18.7	.955	6930	7.5	.383
33	2710	19.4	.990	7000	8.0	.408
34	2650	19.7	1.005	7090	8.6	.440
(left)						
5°	6475	3.0	.153	5985	1.0	.051
8	6760	4.8	.245	6020	1.2	.061
10	6960	6.0	.306	6060	1.5	.076



# TYPICAL DATA SHEET

Rubber: 0% Rubber

Water temperature: 65°F - Water speed: 9 ft/sec. - Date: 3/20/50

Rubber Angle (right) °	Gauge LT Reading	Lift Force	CL	Gauge LT Reading	Drag Force	CD
0	2900	0.0	0.000	2900	0.0	.041
2	2725	1.4	.001	2940	0.2	.041
4	2540	2.7	.017	2970	0.4	.046
6	2350	3.7	.150	3000	1.1	.050
10	2035	5.4	.150	3030	1.3	.060
12	1770	7.1	.302	3050	1.4	.071
14	1520	8.8	.440	3110	1.8	.083
16	1280	10.7	.570	3180	2.4	.112
20	1070	17.7	.800	3200	3.0	.123
24	900	23.2	.970	3260	3.2	.144
26	740	29.0	1.10	3340	4.2	.160
28	590	34.0	1.40	3370	5.0	.181
30	430	37.2	1.60	3400	6.0	.221
32	280	40.1	1.80	3430	7.2	.263
34	130	42.7	2.00	3490	8.0	.400
(36) 0	0	44.7	2.00	3500	8.0	.440
38	0	47.0	2.10	3500	8.0	.501
40	0	49.0	2.20	3500	8.0	.501
42	0	51.0	2.30	3500	8.0	.510

### SAMPLE CALCULATION

From "Sample Data Sheet" on page 45, for 20° right rudder,

$$\text{Lift Force} = 11.7 \text{ lbs.}$$

$$\text{Drag Force} = 3.0 \text{ lbs.}$$

$$\text{Water density (at 62° F)} = \rho = 1.9379 \frac{\text{lb. sec}^2}{\text{ft}^4}$$

$$\text{Rudder area} = S = 0.25 \text{ ft}^2$$

$$\text{Water speed} = V = 9.0 \text{ ft/sec.}$$

$$\text{Lift Coefficient} = C_L = \frac{F_L}{1/2 \rho S V^2} = \frac{11.7}{1/2 (1.9379) (0.25) (81)} = 0.596$$

$$\text{Drag Coefficient} = C_D = \frac{F_D}{1/2 \rho S V^2} = \frac{3.0}{1/2 (1.9379) (0.25) (81)} = 0.153$$

# SAMPLE CALCULATION

From "Sample Data Sheet", on page 45, for 10° right rudder.

$$\text{Lift Force} = 11.7 \text{ lbs.}$$

$$\text{Drag Force} = 3.0 \text{ lbs.}$$

$$\text{Water density (at 60° F)} = 62.3 \text{ lb./cu. ft.}$$

$$\text{Rudder area} = 8.5 \text{ sq. ft.}$$

$$\text{Water speed} = V = 9.0 \text{ ft./sec.}$$

$$\text{Lift Coefficient} = C_L = \frac{L}{\frac{1}{2} \rho V^2 A} = \frac{11.7}{\frac{1}{2} (62.3) (9.0)^2 (8.5)} = 0.006$$

$$\text{Drag Coefficient} = C_D = \frac{D}{\frac{1}{2} \rho V^2 A} = \frac{3.0}{\frac{1}{2} (62.3) (9.0)^2 (8.5)} = 0.002$$

APPENDIX "D"

APPENDIX "D"

THE UNITED STATES OF AMERICA

DEPARTMENT OF THE INTERIOR

BUREAU OF LAND MANAGEMENT

WATER RESOURCES DIVISION

APPENDIX "D"

ORIGINAL DATA

The original data is in the custody of Professor S. Curtiss Powell.

ORIGINAL DATA

The original data is in the custody of Professor S. Curtis Powell.

APPENDIX "E"



ORIGINAL DATA

The original data is in the custody of Professor E. Charles Howell.

APPENDIX "F"

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**DATE DUE**

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Thesis 12863  
E8 Eversole  
Semi-flexible self  
varying camber rudder.

Thesis 12863  
E8 Eversole  
Semi-flexible self  
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